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-Technical Report-

# Fire Resistant Fuel
## Interim Report
## TFLRF No. 416

by
Steven R. Westbrook, Edwin A. Frame, Bernard R. Wright
Steven D. Marty, Adam C. Brandt, Gregory Hansen
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U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

by
Joel Schmitigal

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan
Contract No. W56HZV-09-C-0100 (WD03)

**DISTRIBUTION STATEMENT A.** Approved for public release; distribution is unlimited.

December 2011

15 December 2011

U.S. Army Tank Automotive Research,
Development, and Engineering Center
Detroit Arsenal
Warren, Michigan 48397-5000

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| **14. ABSTRACT**<br>This report presents an overview of the main development areas associated with formulating an optimal Fire Resistant Fuel. The areas will include fuel fire resistance, equipment performance impacts, and also fuel stability and applications. Differences between a JP-8 and a Diesel 2 fuel formulations will also be discussed. This project documented the successful formulation and evaluation of Fire Resistant Fuel. | | | |
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# EXECUTIVE SUMMARY

During an Army–sponsored research program in the mid-1980s, fire-resistant diesel fuel that self extinguished when ignited by an explosive projectile was formulated. This fire resistant fuel (FRF) was a stable mixture of 78% diesel fuel, 10% purified water containing less than 50 ppm dissolved solids, 6% emulsifier, and 6% aromatic hydrocarbon concentrate to aid in the solubility of the emulsifier.

Previous research, including the program headed by the Army in the 1980's, involved using a variety of approaches to reduce the flammability of fuel. These approaches evaluated emulsified fuel, halogenated additives, mist control additives, and water-in-fuel emulsions, the latter showing the most promise, for ground vehicle applications. This fire resistant fuel was a clear to hazy emulsion, consisting of water, emulsifier premix (equal amounts of the emulsifier and an aromatic concentrate), and diesel fuel. This emulsion performed satisfactorily both in diesel and turbine engine systems and could be prepared in the field for availability as needed. Although this earlier version of FRF did not eliminate the initial mist fireball that occurs when a projectile impacts the vehicle, it significantly reduced the fuel fire threat by retarding the flame-spread rate and would self extinguish any spilled fuel and thereby eliminating residual pool burning. The self-extinguishing characteristic of the fuel resulted from:

- the heat sink provided by the water,
- emulsified water on the surface of the fuel preventing fuel vaporization,
- and the released water vapor concentrating at the surface of the fuel eliminating oxygen from the fuel.

By 1987, the urgency for the development of a fire resistant fuel had diminished which resulted in the reallocation of funding. Additionally, there were both technical and logistical reasons for this. Use of the fuel at low temperatures caused ice to form and plug fuel filters. The purity of the water needed to ensure a stable emulsion was considerably higher than the standard level typically generated by the Army's water purification units. These were just two of the major

technical hurdles that the FRF program was unable to clear. The logistical burden associated with the additives required to create the FRF was also an obstacle. Because of a combination of these problems associated with FRF further, efforts to pursue FRF were discontinued.

***FRF Development Project***

With the start of the conflicts in Iraq and Afghanistan, attention once again returned to the fuel fire threat that was taking its toll on both personnel and vehicles. The Army uses JP-8 aviation fuel in ground vehicle operations during combat situations as intended by the single fuel on the battlefield policy. The policy comes from DoD Directive 4140.43, titled "Fuel Standardization," which mandates the use of JP-8 for air and ground forces. The shift to JP-8 enabled the Air Force and the Army to standardize on one single fuel for all operations. The Air Force made this move to increase safety by moving away from JP-4, among other reasons. In contrast, the Army’s move to use JP-8 was primarily made to simplify fuel logistics. JP-8 is a kerosene-based, middle distillate fuel. It typically contains a distribution of hydrocarbons having between 8 and 16 carbon numbers. The specification-required, minimum flashpoint is 38°C (100°F). Diesel fuel, DF-2, by comparison, is a middle distillate fuel composed of a mixture of hydrocarbons with typically between 12 and 21 carbon atoms per molecule. The specification minimum flashpoint temperature of DF-2 is 52°C (125°F).

The flashpoint and light end component differences between diesel and JP-8 are obstacles to the development of a fire-resistant JP-8 formulation that will self extinguish at temperatures reached during desert operating conditions, i.e., up to 65°C (149°F). The higher volatility of JP-8 means that there is more vapor above the fuel within the vehicle’s fuel tank, at any given temperature, compared to a less-volatile fuel like DF-2.

Additionally, most diesel engines utilize fuel as a cooling agent for the engines’ fuel injection system and have a fuel delivery system that returns a portion of the fuel from the injectors back to the fuel tank. This recirculation heats the fuel, commonly raising the temperature of the fuel in the tank, often above its’ flash point, making the fuel more susceptible to ignition.

The heating of the fuel used in compression ignition engines, when combined with any direct or indirect ballistic penetration near the fuel tank or fuel line, significantly increases the potential for a catastrophic fuel fire. Having a fuel that would have less tendency to ignite under these conditions has obvious benefits in terms of increased survivability of both personnel and vehicles.

In April 2007, a more comprehensive effort was initiated that involved the following tasks:

- develop new emulsified fuel formulations;
- investigate mist control additives to diminish the fuel mist fireball;
- determine the effect of FRF on vehicle and equipment systems;
- design a blending system for producing FRF in the field;
- determine overall effectiveness of the FRF based on JP-8.

This report presents an overview of the main development areas associated with formulating an optimal FRF. The areas include fuel fire resistance, equipment performance impacts, and also fuel stability and applications. Differences between JP-8 and DF-2 fuel are also discussed.

The vehicle fuel fires experienced in combat situations occur in two distinct phases. The first phase is commonly termed a fireball and seen as a fuel explosion. The fireball phase is caused by the explosive or ordnance rupturing the fuel tank and performing a rapid mechanical mixture of fuel spray and air, which combined with the heat from the explosive or ordnance manifests itself as an explosion. The second phase is the ignition and flame spread over the pool of fuel from the vehicles' fuel tank. The pool fire is caused by the pool of fuel having a sufficient temperature to vaporize into the air above the pool surface and thus sustain a fire.

Due to the increased volatility of the JP-8 fuel when compared to diesel fuel it is imperative to suppress both phases of these fires since water alone, at acceptable concentrations of water, does not provide sufficient extinguishment. Therefore the goal of the development of a fire resistant JP-8 was to minimize both phases of these fuel fires.

Ballistic testing was used to evaluate FRF formulations. In order to simulate battlefield, fuel tank conditions, in a worst case/hot environment, the ballistic tests were conducted with the FRF pre-heated to 65°C (149°F).

To quantify the “fire resistance” effectiveness of a particular FRF formulation during ballistics testing, a data acquisition system was used to record temperature versus time measurements. The system consisted of 10 thermocouples spread out linearly across the testing area (just above the 30 gallon steel barrel containing the target FRF). Temperature response during testing was recorded at a logging rate of 5kHz for a total of 30 seconds. This information allowed for the determination of the flame propagation rate and severity of the initial fireball and resulting burn where applicable.

To combat the fireball phase of the fire, we conducted fuel formulation work to evaluate the mitigation properties of potential mist control additives. These additives have long chain polymers that act to control fluid droplet size by imparting non-Newtonian properties into the fuel. This, in turn, decreases the surface to volume ratio of the mist droplets and thus reduces the size of the initial fireball. Testing showed that these long chain, high molecular weight additives can reduce the initial fireball. Engine testing was also conducted to determine the degree to which these large molecules would shear down to a smaller size when exposed to the high pressure injection systems of modern diesel engines.

After the initial fireball, the water emulsion works to extinguish the fuel pool fire by means of the heat sink, prevention of fuel vaporization, and elimination of oxygen as described earlier. The mist control additives do not provide any fire suppression properties in the fire pool phase.

For any given FRF, the base fuel used in the FRF has a significant impact on the ability of the fuel to self extinguish. The JP-8 fuel specification (MIL-DTL-83133F) calls for a minimum flashpoint of 38°C. But the actual flashpoint of a given fuel can be above 60°C. Because of the wide range of acceptable JP-8 flashpoint temperatures, the FRF formulation must be designed to perform on the lowest flashpoint fuels encountered. In contrast, using a base fuel with as high of a flashpoint as possible allows for greater extinguishment characteristics to be imparted.

Engine dynamometer testing was performed using multiple engine families commonly used in Army vehicles. Testing was conducted to look at engine horsepower, torque and fuel consumption. In summary, the addition of water to the JP-8 fuel lowers the maximum torque and horsepower while increasing fuel consumption. This is not unexpected as any addition of water to the fuel lowers the overall energy content of the fuel. The mist control additive does add a very small amount of energy back into the fuel, but it is nearly negligible. FRF fuel with 10% water and 250 ppm mist control additive would be expected to provide roughly 8-9 percent less power, torque and fuel economy than neat JP-8.

While desirable for FRF to not have any performance impacts on vehicle operation, the data produced in this research program provided results similar to previous FRF research programs. Power and range losses with FRF use, while undesirable, are unavoidable as any addition of water to the fuel lowers the overall energy content of the fuel. While the drawbacks of these effects may preclude the use of FRF in all ground vehicles at all times, there may be appropriate times when commanders would see benefits in the use of FRF. Utilization of a base fuel with greater energy density, such as diesel fuel No. 2 will offset the power loss experience by FRF JP-8.

Engine data from existing vehicle performance prediction models was used to predict the effects of the FRF on overall vehicle performance. The models showed that effects on vehicle response would be minimal. Individual vehicle operators may notice little difference in fuel energies.

Emulsions can be broadly segregated in two groups, micro and macro-emulsions. These groups differ by the size of the suspended water droplets. Most of the emulsions evaluated in this study were micro-emulsions which provided a clear and bright mixture. Macro-emulsions appeared white and milk like rather than clear/transparent. While the macro-emulsion is not visually clear and bright, the functional performance of a non-stratified opaque FRF mixture is equivalent to clear FRF.

For this study, emulsion stability was defined by the absence of any distinct layers in the FRF mixture. Testing was conducted to statistically optimize and quantify FRF emulsion stability.

Variables included: temperature (hot or cold), base fuel, amount and type of emulsifier, amount and quality of water, and amount and type of mist control additive. Testing also included extended hot and cool storage, and material compatibility studies. Some stratified samples re-mixed with minor agitation, but most did not.

Indefinite emulsion stability is desired, but not likely. Therefore, with limited stability and operational use limits, the present expected deployment of FRF blending is at re-fueling points that fuel vehicles involved in high threat missions. The requirements for this preliminary design have been one that maximizes use of existing Army petroleum and water handling equipment already available within the inventory. Different configurations of the necessary pumping and mixing equipment were considered. However, use of a dedicated pump per fluid (i.e., water, fuel, and emulsifier/additive) that forces each through a static mixer was the preferred approach.

## FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period March 2009 through December 2011 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Allen Comfort and Mr. Eric Sattler (AMSRD-TAR-D/MS110) served as the TARDEC contracting officer's technical representatives.

The authors would like to acknowledge the contribution of the TFLRF technical support staff along with the administrative and report-processing support of the TFLRF administrative staff.

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AMA | Anti-Misting Agent |
| CAT | Caterpillar |
| DEA | Diethanolamine |
| EDTA | Ethylenediamine Tetraacetic Acid |
| EO | Ethylene Oxide |
| FAWPSS | Forward Area Water Point Supply System |
| FMTV | Family of Medium Tactical Vehicles |
| FRF | Fire Resistant Fuel |
| GEP | General Engine Products |
| GPH | Gallons Per Hour |
| GPM | Gallons Per Minute |
| HEMTT-LHS | Heavy Expanded Mobility Tactical Truck-Load Handling System |
| HLB | Hydrophilic Lipophilic Balance |
| HMMWV | High Mobility Multipurpose Wheeled Vehicle |
| IC | Internal Combustion |
| IPDS | Inland Petroleum Distribution System |
| NEMA | National Electrical Manufacturers Association |
| MAD | Mileage Accumulation Dynamometer |
| MCA | Mist Control Agents |
| MRAP | Mine Resistant Ambush Protected |
| OST | Oil Sump Temperatures |
| ROWPU | Reverse Osmosis Water Purification Unit |
| SMFT | Semi trailer Mounted Fabric Tank |
| TARDEC | Tank-Automotive RD&E Center |
| TFLRF | TARDEC Fuel and Lubricants Research Facility |
| TWDS | Tactical Water Distribution System |
| TWV | Tactical Wheeled Vehicle |
| ULSD | Ultra Low Sulfur Diesel |

# 1.0 INTRODUCTION & BACKGROUND

During an Army–sponsored research program in the mid-1980s, fire-resistant diesel fuel that self extinguished when ignited by an explosive projectile was formulated. This fire resistant fuel (FRF) was a stable mixture of 78% diesel fuel, 10% purified water containing less than 50 ppm dissolved solids, 6% emulsifier, and 6% aromatic hydrocarbon concentrate to aid in the solubility of the emulsifier.

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By 1987, the urgency for the development of a fire resistant fuel had diminished, resulting in the reallocation of funding. Additionally, there were both technical and logistical limitations to use of the fuel. Use of the fuel at sub-freezing temperatures cause ice to form and plug fuel filters/screens. The purity of the water needed to ensure a stable emulsion was considerably higher than the standard level of purity typically generated by the Army's water purification units. These were just two of the technical hurdles that the FRF program was unable to clear. The logistical burden associated with the additives required to create the FRF was also an obstacle. Because of these problems associated with FRF, further efforts with FRF were discontinued.

With the start of the conflicts in Iraq and Afghanistan, attention once again returned to the fuel fire threat that was taking its toll on both personnel and vehicles. The Army uses JP-8 aviation fuel in ground vehicle operations during combat situations as intended by the single fuel on the battlefield policy. The policy comes from DoD Directive 4140.43, titled "Fuel Standardization," which mandates the use of JP-8 for air and ground forces. The shift to JP-8 enabled the Air Force and the Army to standardize on one single fuel for all operations. The Air Force made this move to increase safety by moving away from JP-4, among other reasons. In contrast, the Army's move to use JP-8 was primarily made to simplify fuel logistics. JP-8 is a kerosene-based, middle distillate fuel. It typically contains a distribution of hydrocarbons having between 8 and 16 carbon numbers. The specification-required, minimum flashpoint is 38°C (100°F). Diesel fuel, DF-2, by comparison, is a middle distillate fuel composed of a mixture of hydrocarbons with typically between 12 and 21 carbon atoms per molecule. The specification minimum flashpoint temperature of DF-2 is 52°C (125°F).

The flashpoint and light end component differences between diesel and JP-8 are obstacles to the development of a fire-resistant JP-8 formulation that will self extinguish at temperatures reached during desert operating conditions, i.e., up to 65°C (149°F). The higher volatility of JP-8 means that there is more vapor above the fuel within the vehicle's fuel tank, at any given temperature, compared to a less-volatile fuel like DF-2.

Additionally, most diesel engines utilize fuel as a cooling agent for the engines' fuel injection system and have a fuel delivery system that returns a portion of the fuel from the injectors back to the fuel tank. This recirculation heats the fuel, commonly raising the temperature of the fuel in the tank, often above its' flash point, making the fuel more susceptible to ignition.

The heating of the fuel used in compression ignition engines, when combined with any direct or indirect ballistic penetration near the fuel tank or fuel line, significantly increases the potential for a catastrophic fuel fire. Having a fuel that would have less tendency to ignite under these conditions has obvious benefits in terms of increased survivability of both personnel and vehicles.

In April 2007, a more comprehensive effort was initiated that involved the following tasks:

- develop new emulsified fuel formulations;
- investigate mist control additives to diminish the fuel mist fireball;
- determine the effect of FRF on vehicle and equipment systems;
- design a blending system for producing FRF in the field;
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This report presents an overview of the main development areas associated with formulating an optimal FRF. The areas include fuel fire resistance, equipment performance impact, and also fuel stability and applications. Differences between JP-8 and DF-2 fuel are also discussed.

## 2.0 OBJECTIVE

Under this project, work was conducted to optimize and quantify operational stability, use limits, and self-extinguishing abilities of FRF made with both DF-2 and JP-8. Initially a new baseline had to be established (for both blending and flammability) using JP-8, as previous work had only evaluated DF-2. The development of an emulsified fuel formulation that yields a stable emulsion using JP-8 (or diesel fuel) was expected to be the most difficult of all the above tasks. A deeper understanding of variables such as fuel composition, aromatic content, water quality, emulsifier/surfactant chemistry, and additive interactions was needed. Adding to the complexity of this task was the use of mist control additives (long chain, high molecular weight polymers) in the emulsified fuel formulation to control fuel mist droplet size and thus reduce the size of the initial fireball that occurs.

# 3.0 RESULTS & DISCUSSION

Due to the size, scope, and duration of this project, an enormous amount of data was generated. Much of the data is included in this report. However, in some cases, separate reports covering specific tasks have been written. In those instances, this report contains a summary of the report as well as a reference to that report.

## 3.1 FORMULATION STUDIES

***Emulsifiers Literature Review***

Twenty-six patent documents, as summarized in Table 1, that cover emulsifier chemistry as it pertains to water in fuel (hydrocarbon) emulsions were reviewed. These patents span a period of time from 1938 to 2005. Most of these documents were issued U.S. patents. However, some European patents, world patent applications, and U.S. patent applications were also found. The patent search was ended when the classes of identified emulsifier chemistry became repetitious, with no new compound classes being discussed. Eleven of these patent documents pertain to aspects of the Lubrizol technology that has been marketed under the brand name of PuriNOx™[1]. As expected, all identified emulsifier compounds possess structures with a non-polar hydrocarbon section and a polar section. The polar sections invariably contain moieties with nitrogen, oxygen or both. Almost all of the emulsifier chemistry identified in this patent literature represents multi-component systems as opposed to single emulsifier compounds. One common theme that pervades the literature is an emulsifier system that contains one component with minimal polar moieties (relatively lipophilic) and one component with additional polarity in the form of repeated nitrogen and/or oxygen linkages (relatively hydrophilic). The hydrophilic/lipophilic balance (HLB) is a relative parameter that measures to what extent an emulsifier will associate preferentially with aqueous or non-polar media. HLB has values ranging between 1 and 40, with lower values representing lipophilic behavior, and higher

[1] According to EPA fuel registration documents, PuriNOx consists of diesel fuel, water and Lubrizol additives blended to form a stable, homogeneous emulsion. The registered warm-climate formulation contains 77% diesel fuel, 20% water, and 3% PuriNOx 1121A additive package. The winter formulation consists of 74% diesel fuel, 16.8% water, 5.7% methanol, and 3.5% PuriNOx generation 2 additive package.

numbers representing hydrophilic behavior. Accordingly, many of the cited emulsifier systems comprised of a combination of at least one component with a lower HLB value and with at least one component with a higher HLB value.

**Table 1. Emulsifier Patent Summary**

| Emulsifier Component Structure | Supplier Name | Component Commercial Name | Patent Document Citing |
|---|---|---|---|
| polya koxylated phenols | Not given | Nonidet P80 | US 3,756,794 |
| | Not given | Triton X-102 | US 3,756,794 |
| | Not given | Tergitol NP-9-15 | WO 98/56878 |
| | Seppic | Octarox | US 6,068,670 |
| | Sidobre-Sinnova | Sinnopal OP | US 6,068,670 |
| | Rhone Poulenc | Igepal CO-430 | US 6,280,485 |
| polya koxylated a kyl alcohols | Shell | Neodol 23-6.5 | US 4,744,796; US 6,280,485 |
| | Air Products | Surfynol | US 4,744,796 |
| | BASF | Pluronic R | US 6,280,485 |
| polyethoxylated esters | Union Derivan SA | Tilol 163 | US 6,068,670 |
| | Hoeshst | Emulsogen A | US 6,068,670 |
| | Stepan | Secoster MO 400 | US 6,068,670 |
| | Ceca | Remcopal | US 6,068,670 |
| | Seppic | Simulsol M45 | US 6,068,670 |
| | ICI | MYRJ 45 | US 6,068,670 |
| | Auschem SpA | Cerex EL 4929 | US 6,068,670 |
| | Huls, AG, Stepan | Marlosol R70 | US 6,068,670 |
| | Calgene Chemical | Polysorbates | US 6,280,485 |
| | ICI | Tweens | US 6,280,485 |
| Sorbitan esters | ICI | Span 83; Span 20 | US 6,068,670 |
| | ICI | Arlacel 83; Arlacel 20; Arlacel 60 | US 6,068,670 |
| | Rhone Poulenc | A kamuls SML; Alkamuls SMS | US 6,068,670 |
| Quaternary ammonium salts of fatty acids | Armak Chemicals | Arquad | US 4,744,796 |
| Cocoamidobetaine | Emery Industries | Emery 5430; Emery 6748 | US 4,744,796 |
| ethanolamides of fatty acids | not given | Mazamide SS-10 | WO 98/56878 |
| | not given | Schercomide SO-A | US 6,280,485 |

## ***Emulsifier Evaluation Plan***

Each emulsifier system was evaluated for emulsion stability. A precisely defined emulsion stability test protocol was not readily found in the literature. The literature does consistently claim that smaller water droplet size tends to promote higher emulsion stability. Therefore, all other things being constant, smaller water droplet size may indicate better emulsion stability. Accordingly, water droplet size profile that remains good over temperature sweeps was used as a stability indicator. Bench stability testing over a period of two weeks was adopted as a test

period. During the two-week period, at room temperature the pass/fail criterion was defined as no separation or visible change in appearance.

### 3.2 GENERAL EMULSION PROPERTIES

For the purposes of this study, all emulsions contained 10% (vol) water. The water used was the water composition containing 1000 ppm of total dissolved solids (hard water) as determined by the Army's current water purification capabilities. All emulsifier systems were pre-diluted with 50%(wt) of Exxon Aromatic 200. This accomplished two things: 1) the viscosity of the emulsifier system was greatly reduced, allowing easier mixing of the emulsifier system with the fuel, and 2) the increased aromatic content enhanced the stability of the resulting emulsion. Once a few highly effective emulsifier systems were identified, analogous systems substituting Aromatic 150 for Aromatic 200 were prepared to test whether the heavier aromatic material was the optimum one. While Exxon Aromatic 150 was also found acceptable, the heavier Aromatic 200 performed better due to its higher molecular weight. For each emulsifier system that showed promise, a set of emulsions was prepared using that emulsifier system with water and with water containing 0.01%(wt), 0.1%(wt), and 1.0%(wt) of ammonium nitrate (percentages based on the total weight of the water in the emulsion). This was done because of significant evidence in the literature of improved emulsion stability with the addition of ammonium nitrate.

The following is a list of emulsifier systems taken from the patent literature that were evaluated as the first set from which further evaluations were based. Each of the following seven systems are based on one patent, several patents, or a cross combination of technology from several patents. The involved patent numbers are provided for each system. The seven emulsifier systems are listed on the following page:

1. Ammonium salt of fatty acid (oleic) + the fatty acid. (US 3,902,869)
2. Ammonium salt of fatty acid (oleic) + polyalkoxylated phenol. (US 2,111,100; US 3,346,494; US 4,002,435)
3. Reaction product of amino alcohol and fatty acids (salt formation). (US 4,451,265)
4. System 3 (above) + polyalkoxylated phenols. (US 3,346,494 + US 3,756,794)

5. Spans + Tweens. (US 4,477,258 + US 6,068,670)
6. System 5 (above) + ammonium salts of fatty acids (oleic). (US 4,002,435 + US 4,477,258)
7. Reaction product of C18 carboxylic acids (oleic) or sulfonic acids with polyalkoxylated alkyl amine. (EP 475,620)

***Emulsifier Test Matrix***

Table 2 shows the list of emulsifier components. Our initial efforts focused on generating emulsions from single-component blends of some of the emulsifiers listed in Table 2; subsequent testing included multi-component blends. The initial, single-component blends were prepared using 6% emulsifier, 6% Exxon Aromatic 200, and 10% of a 1% saltwater solution. The 1% saltwater solution was selected as a worst case water quality, to test the emulsion stability of the emulsifiers. The fuel types used for these initial blends included a high aromatic diesel fuel (~30%), a low aromatic diesel fuel (~10%), and a Jet A/JP-8.

**Table 2. Emulsifier List**

| Product | HLB Value | Emulsifer Type |
|---|---|---|
| Arlacel 20 | 8.6 | Sorbitan Ester (monolaurate) |
| Arlacel 83 | 3.7 | Sorbitan Ester (sesquioleate) |
| Arquad 2C-75 | 17 | Quaternary ammonium |
| Emulpon CO-360 | N/A | Ethoxylated castor oil |
| Myrj 45 | 11.1 | Polyethoxylated ester (stearate) |
| Neodol N23-1 | 3.7 | Polyalkoxylated alkyl alcohol |
| Neodol N23-2 | 6.5 | Polyalkoxylated alkyl alcohol |
| Neodol N25-1.3 | 4.3 | Polyalkoxylated alkyl alcohol |
| Neodol N25-2.5 | 7.1 | Polyalkoxylated alkyl alcohol |
| Neodol N25-3 | 7.5 | Polyalkoxylated alkyl alcohol |
| Neodol N91-2.5 | 8.1 | Polyalkoxylated alkyl alcohol |
| Pluronic L101 | 1-7 | block copolymer |
| Pluronic L122 | 1-7 | block copolymer |
| Pluronic L61 | 1-7 | block copolymer |
| Pluronic L81 | 1-7 | block copolymer |
| Schercomid ODA | N/A | Ethanolamide of oleic acid |
| Span 40 | 6.7 | Sorbitan Ester (monopalmitate) |
| Span 60 | 4.7 | Sorbitan Ester (monostearate) |
| Span 80 | 4.3 | Sorbitan Ester (monooleate) |
| Tergitol 15-S-3 | 8.0 | Secondary alcohol ethoxylate |
| Tergitol NP-4 | 8.9 | Polyalkoxylated phenol (nonylphenol) |
| Tergitol NP-9 | 12.9 | Polyalkoxylated phenol (nonylphenol) |
| Triton X-100 | 13.4 | Polyalkoxylated phenol (octylphenol) |
| Triton X-102 | 14.4 | Polyalkoxylated phenol (octylphenol) |
| Triton X-114 | 12.8 | Polyalkoxylated phenol (octylphenol) |
| Triton X-15 | 4.9 | Polyalkoxylated phenol (octylphenol) |
| Triton X-35 | 7.8 | Polyalkoxylated phenol (octylphenol) |
| Triton X-45 | 9.8 | Polyalkoxylated phenol (octylphenol) |
| Tween 20 | 16.7 | Polyethoxylated ester (monolaurate) |
| Tween 21 | 13.3 | Polyethoxylated ester (monooleate) |
| Tween 40 | 15.6 | Polyethoxylated ester (monopalmitate) |
| Tween 60 | 14.9 | Polyethoxylated ester (monostearate) |
| Tween 65 | 10.5 | Polyethoxylated ester (tristearate) |
| Tween 80 | 15.0 | Polyethoxylated ester (monooleate) |
| Tween 81 | 10.0 | Polyethoxylated ester (monooleate) |
| Tween 85 | 11.0 | Polyethoxylated ester (trioleate) |
| Oleic Ester | N/A | w/ ethanolamine<br>w/ diethanolamine<br>w/ triethanolamine |

Table 3 shows the fuel/water blends prepared. These blends contained 6% emulsifier, 6% Exxon Aromatic 200,10% of the 1% saltwater solution, and the fuel indicated in the table. These blends were prepared using a mechanical stirrer to overcome the initial increase in viscosity upon water addition. The water was added drop-wise to a stirred solution of the fuel/emulsifier and each blend was stirred for a total of 30 minutes.

**Table 3. Fuel/Water Blends**

| Sample ID | Emulsifer | HLB | Fuel Type | Sample Condition | Recommendation |
|---|---|---|---|---|---|
| FRF0001 | Pluronic L101 | 1.0 | H_30Diesel | - | no further testing |
| FRF0002 | Pluronic L122 | 1.0 | H_30Diesel | - | no further testing |
| FRF0003 | Pluronic L61 | 3.0 | H_30Diesel | - | no further testing |
| FRF0004 | Pluronic L81 | 2.0 | H_30Diesel | - | no further testing |
| FRF0005 | Tergitol 15-S-3 | 8.0 | H_30Diesel | 3 phase, H/M/C | no further testing |
| FRF0006 | Tergitol NP-4 | 8.9 | H_30Diesel | 2 phase, C/M | no further testing |
| FRF0007 | Tergitol NP-9 | 12.9 | H_30Diesel | - | no further testing |
| FRF0008 | Triton X-114 | 12.8 | H_30Diesel | - | no further testing |
| FRF0009 | Triton X-15 | 4.9 | H_30Diesel | 2 phase, C/C | no further testing |
| FRF0010 | Triton X-35 | 7.8 | H_30Diesel | 2 phase, H/C | no further testing |
| FRF0011 | Triton X-45 | 9.8 | H_30Diesel | 2 phase, C/M | additional testing |
| FRF0012 | 50% X-15 / 50% X-100 | 9.2 | H_30Diesel | 2 phase, C/M, slow settling | additional testing |
| FRF0013 | 75% X-15 / 25% X-100 | 7.0 | H_30Diesel | 2 phase, H/M | no further testing |
| FRF0014 | 50% X-15 / 50% X-102 | 9.7 | H_30Diesel | - | no further testing |
| FRF0015 | 75% X-15 / 25% X-102 | 7.3 | H_30Diesel | 1 phase, M, no settling | additional testing |
| FRF0016 | 50% X-15 / 50% X-114 | 8.9 | H_30Diesel | 2 phase, H/M | additional testing |
| FRF0017 | 75% X-15 / 25% X-114 | 6.9 | H_30Diesel | 2 phase, C/M | no further testing |
| FRF0019 | 75% X-35 / 25% X-100 | 9.2 | H_30Diesel | 2 phase, C/M | no further testing |
| FRF0021 | 75% X-35 / 25% X-102 | 9.4 | H_30Diesel | 2 phase, H/M | no further testing |
| FRF0023 | 75% X-35 / 25% X-114 | 9.0 | H_30Diesel | 2 phase, C/M | no further testing |
| FRF0030 | 50% X-15 / 50% X-100 | 9.2 | JP8 | 2 phase, C/M, slow settling | additional testing |
| FRF0031 | 75% X-15 / 25% X-100 | 7.0 | JP8 | 2 phase, C/M | no further testing |
| FRF0032 | 50% X-15 / 50% X-102 | 9.7 | JP8 | - | no further testing |
| FRF0033 | 75% X-15 / 25% X-102 | 7.3 | JP8 | 2 phase, C/C | no further testing |
| FRF0034 | 50% X-15 / 50% X-114 | 8.9 | JP8 | 2 phase, H/M | additional testing |
| FRF0035 | 75% X-15 / 25% X-114 | 6.9 | JP8 | 2 phase, C/M | no further testing |
| FRF0037 | 75% X-35 / 25% X-100 | 9.2 | JP8 | 2 phase, C/M | no further testing |
| FRF0039 | 75% X-35 / 25% X-102 | 9.4 | JP8 | 2 phase, C/M | no further testing |
| FRF0041 | 75% X-35 / 25% X-114 | 9.0 | JP8 | 2 phase, C/M | no further testing |
| FRF0048 | Pluronic L101 | 1.0 | JP8 | - | no further testing |
| FRF0049 | Pluronic L122 | 1.0 | JP8 | - | no further testing |
| FRF0050 | Pluronic L61 | 3.0 | JP8 | 3 phase, H/C/C | no further testing |
| FRF0051 | Pluronic L81 | 2.0 | JP8 | - | no further testing |
| FRF0052 | Tergitol 15-S-3 | 8.0 | JP8 | 3 phase, C/M/C | no further testing |
| FRF0053 | Tergitol NP-4 | 8.9 | JP8 | 2 phase, C/M | no further testing |
| FRF0054 | Tergitol NP-9 | 12.9 | JP8 | - | no further testing |
| FRF0055 | Triton X-114 | 12.8 | JP8 | - | no further testing |
| FRF0056 | Triton X-15 | 4.9 | JP8 | 2 phase, C/C | no further testing |
| FRF0057 | Triton X-35 | 7.8 | JP8 | 2 phase, C/C | no further testing |

NOTE: C=Clear, H=Hazy, M=Milky
H30_Diesel = ~30% aromatic diesel
H10_Diesel = ~10% aromatic diesel

# Table 3. Fuel/Water Blends (Continued)

| Sample ID | Emulsifer | HLB | Fuel Type | Sample Condition | Recommendation |
|---|---|---|---|---|---|
| FRF0058 | Triton X-45 | 9.8 | JP8 | 2 phase, C/M | additional testing |
| FRF0059 | Schercomid ODA | N/A | H_30Diesel | 1 phase, hazy | additional testing |
| FRF0060 | Schercomid ODA | N/A | JP8 | 1 phase, hazy | additional testing |
| FRF0061 | Pluronic L101 | 1.0 | H_10Diesel | - | no further testing |
| FRF0062 | Pluronic L122 | 1.0 | H_10Diesel | - | no further testing |
| FRF0063 | Pluronic L61 | 3.0 | H_10Diesel | 3 phase, C/C/C | no further testing |
| FRF0064 | Pluronic L81 | 2.0 | H_10Diesel | - | no further testing |
| FRF0065 | Tergitol 15-S-3 | 8.0 | H_10Diesel | 2 phase, H/C | no further testing |
| FRF0066 | Tergitol NP-4 | 8.9 | H_10Diesel | 2 phase, C/M | no further testing |
| FRF0067 | Tergitol NP-9 | 12.9 | H_10Diesel | - | no further testing |
| FRF0068 | Triton X-114 | 12.8 | H_10Diesel | - | no further testing |
| FRF0069 | Triton X-15 | 4.9 | H_10Diesel | 2 phase, C/C | no further testing |
| FRF0070 | Triton X-35 | 7.8 | H_10Diesel | 2 phase, H/C | no further testing |
| FRF0071 | Triton X-45 | 9.8 | H_10Diesel | 2 phase, C/M | additional testing |
| FRF0072 | Schercomid ODA | N/A | H_10Diesel | 1 phase, hazy | additional testing |
| FRF0073 | 50% X-15 / 50% X-100 | 9.2 | H_10Diesel | 3 phase, C/M/C | no further testing |
| FRF0074 | 75% X-15 / 25% X-100 | 7.0 | H_10Diesel | 2 phase, C/M | no further testing |
| FRF0075 | 50% X-15 / 50% X-102 | 9.7 | H_10Diesel | 2 phase, C/M clumpy | no further testing |
| FRF0076 | 75% X-15 / 25% X-102 | 7.3 | H_10Diesel | 1 phase, Milky, no settling | additional testing |
| FRF0077 | 50% X-15 / 50% X-114 | 8.9 | H_10Diesel | 2 phase, H/M | additional testing |
| FRF0078 | 75% X-15 / 25% X-114 | 6.9 | H_10Diesel | 2 phase, C/M | no further testing |
| FRF0080 | 75% X-35 / 25% X-100 | 9.2 | H_10Diesel | 3 phase, C/M/C | no further testing |
| FRF0082 | 75% X-35 / 25% X-102 | 9.4 | H_10Diesel | 3 phase, C/M/C | no further testing |
| FRF0084 | 75% X-35 / 25% X-114 | 9.0 | H_10Diesel | 2 phase, C/C | no further testing |
| FRF0091 | 50% X-15 / 50% Tergitol NP-9 | 8.9 | H_30Diesel | 2 phase, C/M, slow settling | additional testing |
| FRF0092 | 50% X-15 / 50% Tergitol NP-9 | 8.9 | JP8 | 2 phase, C/M, slow settling | additional testing |
| FRF0093 | 75% X-35 / 25% Tergitol NP-9 | 9.1 | H_30Diesel | 2 phase, C/M | no further testing |
| FRF0094 | 75% X-35 / 25% Tergitol NP-9 | 9.1 | JP8 | 3 phase, C/M/C | no further testing |
| FRF0095 | ethanolamine/oleic 1/1 salt/acid | N/A | H_30Diesel | 2 phase, H/M | no further testing |
| FRF0096 | ethanolamine/oleic 1/1 salt/acid | N/A | JP8 | 2 phase, H/M | no further testing |
| FRF0097 | ethanolamine/oleic 1/0.5 salt/acid | N/A | H_30Diesel | 2 phase, H/M | no further testing |
| FRF0098 | ethanolamine/oleic 1/0.5 salt/acid | N/A | JP8 | 2 phase, M/M | no further testing |
| FRF0099 | ethanolamine/oleic 1/0.1 salt/acid | N/A | H_30Diesel | 2 phase, M/M | no further testing |
| FRF0100 | ethanolamine/oleic 1/0.1 salt/acid | N/A | JP8 | 2 phase, M/M | no further testing |
| FRF0101 | diethanolamine/oleic 1/1 salt/acid | N/A | H_30Diesel | 2 phase, M/M | no further testing |
| FRF0102 | diethanolamine/oleic 1/1 salt/acid | N/A | JP8 | 2 phase, M/M | no further testing |
| FRF0103 | diethanolamine/oleic 1/0.5 salt/acid | N/A | H_30Diesel | 2 phase, M/M | no further testing |
| FRF0104 | diethanolamine/oleic 1/0.5 salt/acid | N/A | JP8 | 2 phase, M/M | no further testing |
| FRF0105 | diethanolamine/oleic 1/0.1 salt/acid | N/A | H_30Diesel | - | no further testing |
| FRF0106 | diethanolamine/oleic 1/0.1 salt/acid | N/A | JP8 | 2 phase, C/M clumpy | no further testing |
| FRF0107 | triethanolamine/oleic 1/1 salt/acid | N/A | H_30Diesel | 2 phase, C/M | no further testing |
| FRF0108 | triethanolamine/oleic 1/1 salt/acid | N/A | JP8 | - | no further testing |
| FRF0109 | triethanolamine/oleic 1/0.5 salt/acid | N/A | H_30Diesel | - | no further testing |
| FRF0110 | triethanolamine/oleic 1/0.5 salt/acid | N/A | JP8 | - | no further testing |
| FRF0111 | triethanolamine/oleic 1/0.1 salt/acid | N/A | H_30Diesel | - | no further testing |
| FRF0112 | triethanolamine/oleic 1/0.1 salt/acid | N/A | JP8 | - | no further testing |
| FRF0113 | 20% X-15 / 80% Schercomid | N/A | H_30Diesel | 2 phase, H/M | no further testing |
| FRF0114 | 20% X-15 / 80% Schercomid | N/A | JP8 | 2 phase, H/M | no further testing |
| FRF0115 | Neodol 25-1 | 3.7 | H_30Diesel | 2 phase, H/C | no further testing |
| FRF0116 | Neodol 25-1 | 3.7 | H_30Diesel | 3 phase, H/M/H | no further testing |
| FRF0117 | Neodol 25-1 | 3.7 | H_30Diesel | 3 phase, H/M/H | no further testing |
| FRF0118 | Neodol 25-2 | 6.5 | JP8 | 2 phase, H/C | no further testing |
| FRF0119 | Neodol 25-2 | 6.5 | JP8 | 3 phase, C/M/H | no further testing |
| FRF0120 | Neodol 25-2 | 6.5 | JP8 | 3 phase, H/M/H | no further testing |
| FRF0121 | Neodol 25-3 | 7.5 | H_10Diesel | 2 phase, C/H | no further testing |
| FRF0122 | Neodol 25-3 | 7.5 | H_10Diesel | 2 phase, C/M | no further testing |
| FRF0123 | Neodol 25-3 | 7.5 | H_10Diesel | 1 phase, milky, thick | no further testing |

NOTE: C=Clear, H=Hazy, M=Milky
H30_Diesel = ~30% aromatic diesel
H10_Diesel = ~10% aromatic diesel

The Schercomid ODA blends (Figure 1), provided the best stability based on the 2 week storage test, and was established as the standard by which we visually compared other product blends. Several blends using the Triton X emulsifiers showed promise for both JP-8 and diesel fuel blends. The photos show the fuels arranged left to right as JP-8, 10% aromatic diesel, and 30% aromatic diesel.


**Figure 1. Schercomid ODA**

The Triton X-45 emulsifier, having an HLB value = 9.8, generated a reasonably stable emulsion in all fuels with minimal settling (Figure 2). Adjusting the final HLB value was possible by blending emulsifiers with varying HLB values in the appropriate concentration. For example, Triton X-15 (HLB=4.9) blended 1:1 with Triton X-114 (HLB = 12.8) generated an emulsion with little settling (Figure 3). The final HLB value of this two-component blend was approximately 8.9.


**Figure 2. Triton X-45**

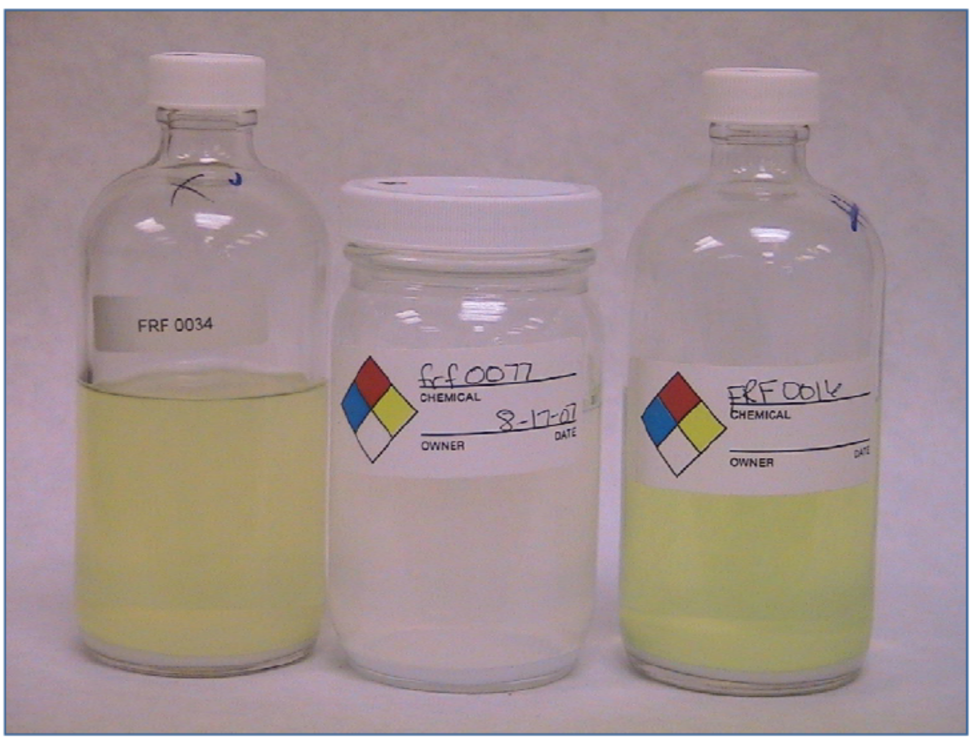



**Figure 3. 50% Triton X-15 / 50% Triton X-114**

For the diesel fuel blends, samples FRF0015 and FRF0076 (75% / 25% X-15 / X-102) were also of interest. Although they appear milky (Figure 4), they showed no signs of settling.


**Figure 4. 75% Triton X-15 / 25% Triton X-102**

We also retained samples FRF0012 and FRF0030 (Figure 5), FRF0092 and FRF0091 (Figure 6). These blends represented samples that settled very slowly over time and were considered useful for a comparison of settling rates. Although not apparent in the photos, there is no bottom layer formation in these blends as is common in many of the other blends that phase separate immediately upon standing.

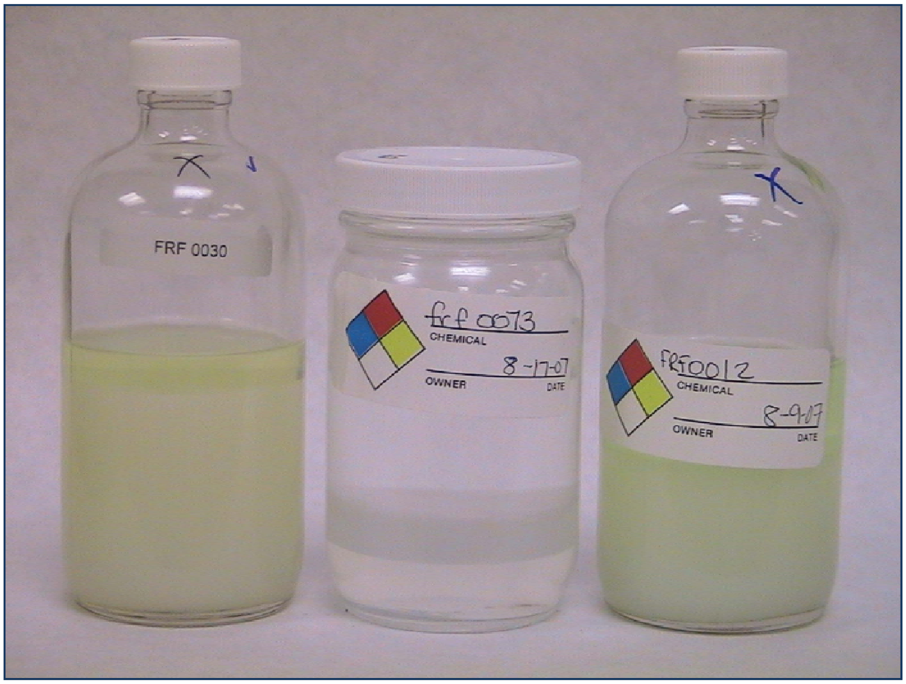



**Figure 5. 50% Triton X-15 / 50% Triton X-100**

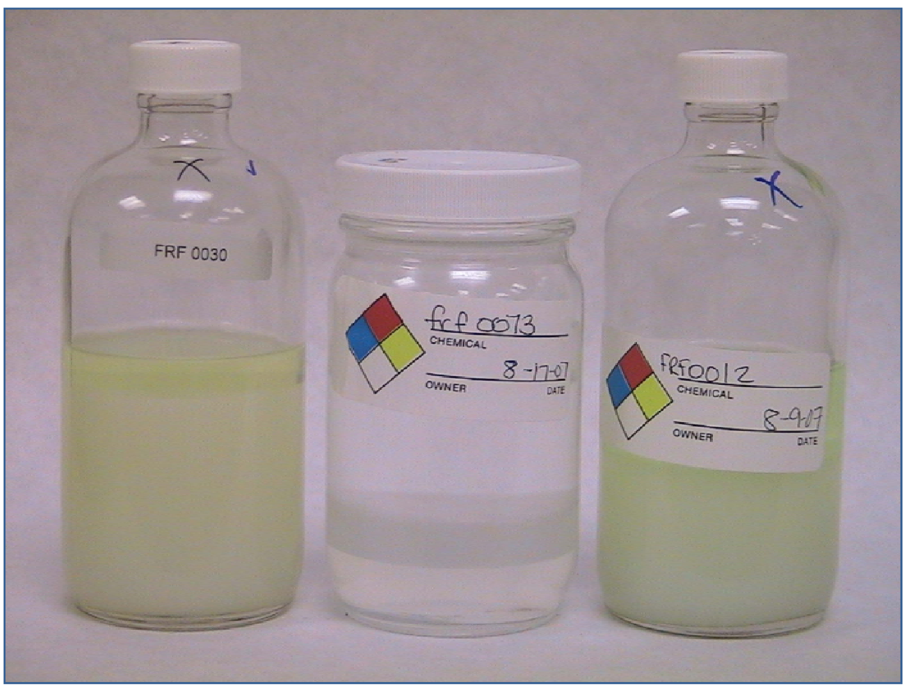



**Figure 6. 50% Triton X-15 / 50% Tergiton NP-9**

Overall, the most promising blends used emulsifiers with HLB values between 7 and 10; however, an emulsifier having an HLB value in this range does not guarantee success, likely

because of the specific chemistry of the emulsifier. The Schercomid (Oleamide diethanolamine) and Triton X (octylphenol ethoxylate) emulsifiers were found to be the best formulations for this application.The ionic emulsifiers (amine salts of oleic acid) and the emulsifiers consisting of normal primary alcohol ethoxylates (Neodol family) did not generate stable emulsions.

We reinvestigated some of the emulsifiers that showed promise after the 2 week stability study by looking at different ratios of the more promising two-component blends. Table 4 shows the new fuel/water blends that were prepared (FRF0124-0147) and prior blends for comparison. As with prior blends, these blends contained 6% emulsifier, 10% of the 1% saltwater solution, 6% Exxon Aromatic 200, and the fuel indicated in the table. These blends were blended for 30 minutes using a mechanical stirrer with drop-wise water addition.

Generally, the improvements were not seen (and in some cases the performance was worse) with the following notable exceptions:

- FRF0140 (JP-8)
- FRF0146 (JP-8)
- FRF0138 (30% Diesel)

These blends showed noticeable improvements in the quality of the emulsion (i.e., slightly hazy to opaque but with less settling). Overall, a general trend became very clear. Modified blend ratios that increased the HLB value from ~7.3 to ~8.3 or decreased the HLB value from 9+ to ~8.3 gave visually better emulsions. In most cases, the best emulsions were still those that consisted of Triton X-15 blended with small quantities of other emulsifiers. All of the new blends containing Triton X-114 appeared worse with significant two-phase separation.

**Table 4. New Fuel/Water Blends**

| Sample ID | Emulsifer | HLB | Fuel Type |
|---|---|---|---|
| FRF0011 | Triton X-45 | 9.8 | H_30Diesel |
| FRF0012 | 50% X-15 / 50% X-100 | 9.2 | H_30Diesel |
| FRF0015 | 75% X-15 / 25% X-102 | 7.3 | H_30Diesel |
| FRF0016 | 50% X-15 / 50% X-114 | 8.9 | H_30Diesel |
| FRF0030 | 50% X-15 / 50% X-100 | 9.2 | JP8 |
| FRF0034 | 50% X-15 / 50% X-114 | 8.9 | JP8 |
| FRF0058 | Triton X-45 | 9.8 | JP8 |
| FRF0059 | Schercomid ODA | N/A | H_30Diesel |
| FRF0060 | Schercomid ODA | N/A | JP8 |
| FRF0071 | Triton X-45 | 9.8 | H_10Diesel |
| FRF0072 | Schercomid ODA | N/A | H_10Diesel |
| FRF0076 | 75% X-15 / 25% X-102 | 7.3 | H_10Diesel |
| FRF0077 | 50% X-15 / 50% X-114 | 8.9 | H_10Diesel |
| FRF0091 | 50% X-15 / 50% Tergitol NP-9 | 8.9 | H_30Diesel |
| FRF0092 | 50% X-15 / 50% Tergitol NP-9 | 8.9 | JP8 |
| FRF0125 | 70% X-15 / 30% X-100 | 7.5 | H_10Diesel |
| FRF0127 | 55% X-15 / 45% X-102 | 9.2 | H_10Diesel |
| FRF0128 | 60% X-15 / 40% X-114 | 8.1 | H_10Diesel |
| FRF0129 | 70% X-15 / 30% X-114 | 7.3 | H_10Diesel |
| FRF0131 | 70% X-15 / 30% Tergitol NP-9 | 7.3 | H_10Diesel |
| FRF0132 | 60% X-15 / 40% X-100 | 8.3 | H_30Diesel |
| FRF0133 | 70% X-15 / 30% X-100 | 7.5 | H_30Diesel |
| FRF0134 | 65% X-15 / 35% X-102 | 8.2 | H_30Diesel |
| FRF0135 | 55% X-15 / 45% X-102 | 9.2 | H_30Diesel |
| FRF0136 | 60% X-15 / 40% X-114 | 8.1 | H_30Diesel |
| FRF0137 | 70% X-15 / 30% X-114 | 7.3 | H_30Diesel |
| FRF0139 | 70% X-15 / 30% Tergitol NP-9 | 7.3 | H_30Diesel |
| FRF0141 | 70% X-15 / 30% X-100 | 7.5 | API_JP8 |
| FRF0142 | 65% X-15 / 35% X-102 | 8.2 | API_JP8 |
| FRF0143 | 55% X-15 / 45% X-102 | 9.2 | API_JP8 |
| FRF0144 | 60% X-15 / 40% X-114 | 8.1 | API_JP8 |
| FRF0145 | 70% X-15 / 30% X-114 | 7.3 | API_JP8 |
| FRF0147 | 70% X-15 / 30% Tergitol NP-9 | 7.3 | API_JP8 |

NOTE: H30_Diesel = ~30% aromatic diesel
H10_Diesel = ~10% aromatic diesel

The following emulsifiers were also evaluated:

- Sorbitan Sesquioleate
- Sorbitan Monooleate
- Polysorbate 20
- Polysorbate 40
- Polysorbate 60

- Polysorbate 80
- Myrj 45

In the literature, sorbitan and polysorbate esters are commonly referred to as spans and tweens, respectively. Myrj 45 is a polyethoxylene (8) stearate. These are common emulsifiers and have shown some merit in the literature. We investigated the use of these in both single and two-component blends.

The Span (and Arlacel) products have HLB<5 while the Tween (and Myrj 45) products have HLB>11. Therefore, based on our prior experience with the other emulsifiers, we investigated blends of these emulsifiers that would yield a final HLB of approximately 8.0. Table 5 shows the fuel/emulsifier/water blends that were prepared (FRF0148-0177) from different combinations of these emulsifiers. As with all prior blends, these blends contained 6% by volume of emulsifier, 6% Exxon Aromatic 200, and 10% by volume of a 1% saltwater solution using the fuel indicated in the table. These blends were blended for 30 minutes using a mechanical stirrer with drop-wise water addition. None of these blends showed any improvement over the previously investigated emulsifiers. All of them were milky in appearance and showed some signs of settling.

**Table 5. Fuel/Emulsifier/Water Blends**

| Sample ID | Emulsifier #1 | | | Emulsifier #2 | | | Calculated HLB | Fuel Type |
|---|---|---|---|---|---|---|---|---|
| | Product | HLB | % | Product | HLB | % | | |
| FRF0148 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 40% | Myrj 45 | 11.1 | 60% | 8.1 | H10_Diesel |
| FRF0149 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 65% | Tween 20, Sorbitan Monolaurate | 16.7 | 35% | 8.3 | H10_Diesel |
| FRF0150 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 65% | Tween 40, Sorbitan Monopalmitate | 15.6 | 35% | 7.9 | H10_Diesel |
| FRF0151 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 60% | Tween 60, Sorbitan Monostearate | 14.9 | 40% | 8.2 | H10_Diesel |
| FRF0152 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 60% | Tween 80, Sorbitan Monooleate | 15 | 40% | 8.2 | H10_Diesel |
| FRF0153 | Span 80, Sorbitan Monooleate | 4.3 | 45% | Myrj 45 | 11.1 | 55% | 8.0 | H10_Diesel |
| FRF0154 | Span 80, Sorbitan Monooleate | 4.3 | 70% | Tween 20, Sorbitan Monolaurate | 16.7 | 30% | 8.0 | H10_Diesel |
| FRF0155 | Span 80, Sorbitan Monooleate | 4.3 | 65% | Tween 40, Sorbitan Monopalmitate | 15.6 | 35% | 8.3 | H10_Diesel |
| FRF0156 | Span 80, Sorbitan Monooleate | 4.3 | 65% | Tween 60, Sorbitan Monostearate | 14.9 | 35% | 8.0 | H10_Diesel |
| FRF0157 | Span 80, Sorbitan Monooleate | 4.3 | 65% | Tween 80, Sorbitan Monooleate | 15 | 35% | 8.0 | H10_Diesel |
| FRF0158 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 40% | Myrj 45 | 11.1 | 60% | 8.1 | H30_Diesel |
| FRF0159 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 65% | Tween 20, Sorbitan Monolaurate | 16.7 | 35% | 8.3 | H30_Diesel |
| FRF0160 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 65% | Tween 40, Sorbitan Monopalmitate | 15.6 | 35% | 7.9 | H30_Diesel |
| FRF0161 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 60% | Tween 60, Sorbitan Monostearate | 14.9 | 40% | 8.2 | H30_Diesel |
| FRF0162 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 60% | Tween 80, Sorbitan Monooleate | 15 | 40% | 8.2 | H30_Diesel |
| FRF0163 | Span 80, Sorbitan Monooleate | 4.3 | 45% | Myrj 45 | 11.1 | 55% | 8.0 | H30_Diesel |
| FRF0164 | Span 80, Sorbitan Monooleate | 4.3 | 70% | Tween 20, Sorbitan Monolaurate | 16.7 | 30% | 8.0 | H30_Diesel |
| FRF0165 | Span 80, Sorbitan Monooleate | 4.3 | 65% | Tween 40, Sorbitan Monopalmitate | 15.6 | 35% | 8.3 | H30_Diesel |
| FRF0166 | Span 80, Sorbitan Monooleate | 4.3 | 65% | Tween 60, Sorbitan Monostearate | 14.9 | 35% | 8.0 | H30_Diesel |
| FRF0167 | Span 80, Sorbitan Monooleate | 4.3 | 65% | Tween 80, Sorbitan Monooleate | 15 | 35% | 8.0 | H30_Diesel |
| FRF0168 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 40% | Myrj 45 | 11.1 | 60% | 8.1 | API_JP8 |
| FRF0169 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 65% | Tween 20, Sorbitan Monolaurate | 16.7 | 35% | 8.3 | API_JP8 |
| FRF0170 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 65% | Tween 40, Sorbitan Monopalmitate | 15.6 | 35% | 7.9 | API_JP8 |
| FRF0171 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 60% | Tween 60, Sorbitan Monostearate | 14.9 | 40% | 8.2 | API_JP8 |
| FRF0172 | Arlacel 83, Sorbitan Sesquioleate | 3.7 | 60% | Tween 80, Sorbitan Monooleate | 15 | 40% | 8.2 | API_JP8 |
| FRF0173 | Span 80, Sorbitan Monooleate | 4.3 | 45% | Myrj 45 | 11.1 | 55% | 8.0 | API_JP8 |
| FRF0174 | Span 80, Sorbitan Monooleate | 4.3 | 70% | Tween 20, Sorbitan Monolaurate | 16.7 | 30% | 8.0 | API_JP8 |
| FRF0175 | Span 80, Sorbitan Monooleate | 4.3 | 65% | Tween 40, Sorbitan Monopalmitate | 15.6 | 35% | 8.3 | API_JP8 |
| FRF0176 | Span 80, Sorbitan Monooleate | 4.3 | 65% | Tween 60, Sorbitan Monostearate | 14.9 | 35% | 8.0 | API_JP8 |
| FRF0177 | Span 80, Sorbitan Monooleate | 4.3 | 65% | Tween 80, Sorbitan Monooleate | 15 | 35% | 8.0 | API_JP8 |

NOTE: H30_Diesel = ~30% aromatic diesel
H10_Diesel = ~10% aromatic diesel

### ***Emulsifier Test Conclusions***

Of all the surfactants tested, Schercomid ODA showed the most promise. Schercomid ODA formed relatively stable emulsions in both diesel and aviation fuel. The primary ingredient in Schercomid ODA is Oleamide DEA (Figure 7) – a fatty acid amide. Schercomid ODA also contains up to 8% of the free oleic acid and up to 25% of the unreacted diethanolamine. Diethanolamine is completely soluble in water and thus we might expect it to partition into the water droplets. This might interfere with the hydrogen bonding that occurs between the water of hydration and the polar head of the surfactant thus destabilizing the emulsion.

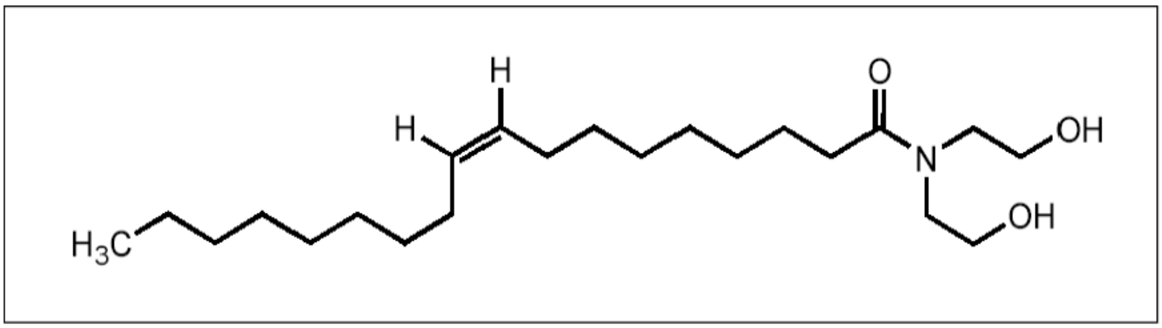



**Figure 7. Oleamide DEA**

### ***Other Emulsifiers Evaluated***

Subtle changes in the chemical structure of emulsifiers can have a significant impact on their physical properties and on the emulsions that they generate. The fully saturated version of Oleamide DEA is known as Stearamide DEA (Figure 8). The presence of a double bond in a long chain fatty acid creates a “kink” that resists efficient packing in solution and prevents crystallization. So, whereas oleic acid (1 unit of unsaturation) has a melting point of 4°C, stearic acid (fully saturated) is a solid at room temperature.

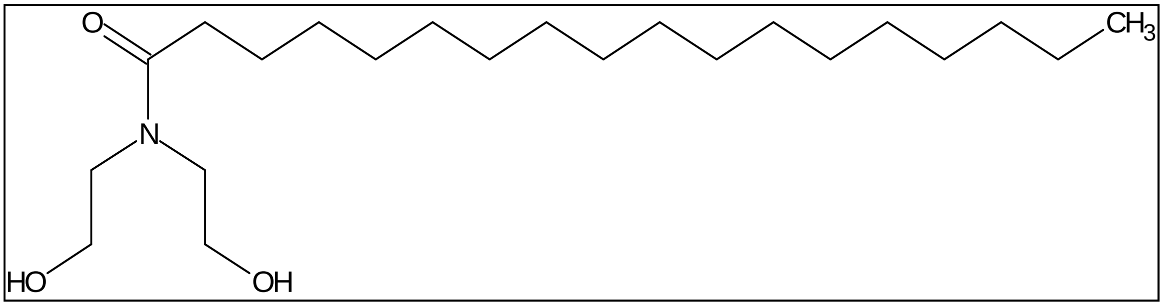



**Figure 8. Stearamide DEA**

In emulsifier chemistry it is known that micelle formation, the speed with which they aggregate, and their stability is strongly dependent on the hydrophobic attraction between the long tails of the surfactant molecules. Taking all of this information together, it might be reasonable to suspect that a fully saturated compound would improve the entanglement of the long fatty chains and thus impart some additional stability to the water droplet. This stability might be at the expense of other performance properties such as the cloud point or perhaps viscosity.

To further characterize these subtle changes in emulsifier chemical structure and their effect on emulsion stability, we acquired some additional surfactant samples. ***Lipamide S (Lipo Chemicals, Inc.)***, a Stearamide DEA (Figure 8), was received and blends were prepared in JP-8 and diesel fuel. Stearamide DEA is a solid, yellow, waxy material at room temperature. We found that heating the fuel (~40°C) on a hot plate helped to speed the dissolution of the Stearamide DEA pellets. Various blends were prepared using 3-6% by weight of the surfactant and 5-10% by volume of the 1% saltwater solution. At low concentration ratios, such as 3% (w) surfactant to 5% (v) of water, a clear emulsion could be generated in diesel fuel. However, this emulsion remained clear only at elevated temperatures. At approximately 24°C, the solution would suddenly become hazy and the water/surfactant would gradually fall out of solution. We found this to be the case in all of the blends we prepared. Therefore, we abandoned further work using this surfactant.

***Schercomid SLE (Noveon)*** is a Linoleamide DEA (Figure 9), which contains two units of unsaturation in the fatty acid backbone. This product claims to have <0.5% free fatty acid and <5% unreacted diethanolamine.

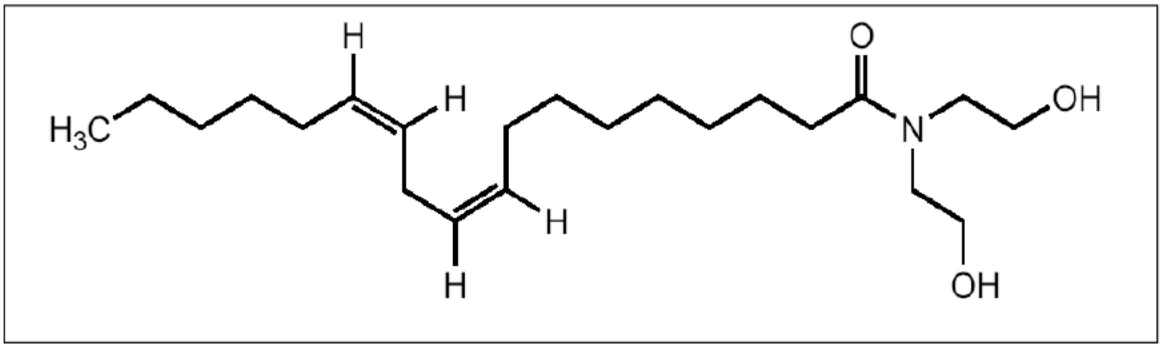



**Figure 9. Linoleamide DEA**

Schercomid SLE (Linoleamide DEA), Figure 10 was received from Lubrizol and blends were prepared in JP-8 and diesel fuel (10% aromatics). Schercomid DEA is a viscous, orange-colored liquid at room temperature and contains no more than 5% free diethanolamine (DEA). While similar to Schercomid ODA, this compound contains an additional unit of un-saturation in the backbone. We speculated that this might increase its solubility at lower temperatures.

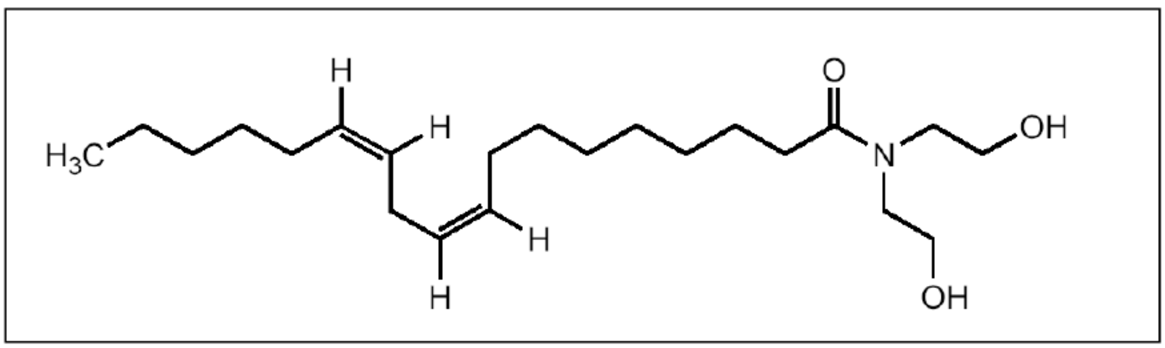



**Figure 10. Schercomid SLE (Linoleamide DEA)**

Neither the SLE/JP-8 nor the SLE/Diesel blend gave satisfactory results. The blends were prepared using 6% by weight of the surfactant and either 4.7% or 9.1% by weight of DI water. Even at low water concentrations, the blends were turbid. Blends prepared at the higher water concentration showed signs of settling almost immediately. Warming the solutions to approximately 35°C had no apparent effect on the blends.

### *Water Hardness / Solids*

At the onset of this project, one of the goals was to develop a formulation that would produce a stable FRF with water that had up to 1000 ppm of dissolved solids. Initial attempts to meet this goal centered around finding an emulsifier that would produce the desired results. Unfortunately, none of the emulsifiers that we evaluated were found to produce an acceptable emulsion with water containing 1000 ppm solids. After an emulsifier was selected, we looked for alternative ways to reach the water hardness goal. Variations of mixing time and energy were investigated without success. Looking for yet another approach, we decided to mix a chelating agent (ethylenediamine tetraacetic acid, EDTA) with the blend. The EDTA chelates the solids and prevents them from inferring with the emulsifier. Through a series of experiments, we found that adding EDTA at a 1:1 ratio, on a ppm basis with the measured solids in the water, yielded a stable emulsion. We obtained acceptable results up to 1250 ppm of dissolved solids. We did not attempt mixing with water above 1250 ppm solids.

## 3.3 EMULSION STABILITY MEASUREMENT

### *Centrifugal Separation*

To get a sense of the stability of the emulsions we performed centrifuge experiments on the blends that visually appeared to be the most stable based on the 2 week room temperature stability study detailed above. These samples ranged from slightly hazy to milky in appearance but with no signs of separation or settling after standing for long periods at room temperature. Based on similar experimentation in the literature[1], the samples were spun at 10,000 rpm (11,963g) for 1 hour at three temperatures: (1) –6.6°C, (2) 23.3°C, and (3) 40°C. **Error! Reference source not found.** summarizes the results from the centrifuge experiments. Under these conditions, most of the emulsions can be forcibly broken. Not unexpectedly, the diesel fuel emulsions were more stable than their JP-8 counterparts. Furthermore, some of the results suggested a temperature dependence showing better stability at either high or low temperature but not both. The Schercomid ODA and 75:25 X-15/X-102 emulsions in 10% aromatic diesel fuel showed the best stability. The same temperature dependence seen in the 30% aromatic diesel fuel was seen here as well.

**Table 6. Centrifuge Experiments**

**Table 6. Centrifuge Experiments**

| Sample ID | Emulsifer | HLB | Fuel Type | 6.6°C (43.9°F) | 23.3°C (73.9°F) | 40°C (104°F) |
|---|---|---|---|---|---|---|
| FRF0011 | Triton X-45 | 9.8 | H_30Diese | Clear fuel / Water Bottom | Clear fuel / Water Bottom | Clear fuel / Water Bottom |
| FRF0012 | 50% X-15 / 50% X-100 | 9.2 | H_30Diese | no separation | Clear fuel / Water Bottom | 3-phase separation |
| FRF0015 | 75% X-15 / 25% X-102 | 7.3 | H_30Diese | no separation | no separation | 2-phase separation |
| FRF0016 | 50% X-15 / 50% X-114 | 8.9 | H_30Diese | Clear fuel / Water Bottom | Clear fuel / Water Bottom | Clear fuel / Water Bottom |
| FRF0030 | 50% X-15 / 50% X-100 | 9.2 | API_JP8 | 2-phase separation | Clear fuel / Water Bottom | 3-phase separation |
| FRF0058 | Triton X-45 | 9.8 | API_JP8 | Clear fuel / Water Bottom | Clear fuel / Water Bottom | Cloudy fuel / Water Bottom |
| FRF0059 | Schercomid ODA | N/A | H_30Diese | Cloudy fuel / Water Bottom | no separation | no separation |
| FRF0060 | Schercomid ODA | N/A | API_JP8 | Clear fuel / Water Bottom | Clear fuel / Water Bottom | Clear fuel / Water Bottom |
| FRF0034 | 50% X-15 / 50% X-114 | 8.9 | API_JP8 | Clear fuel / Water Bottom | Clear fuel / Water Bottom | Clear fuel / Water Bottom |
| FRF0071 | Triton X-45 | 9.8 | H_10Diese | Clear fuel / Water Bottom | Clear fuel / Water Bottom | Cloudy fuel / Water Bottom |
| FRF0072 | Schercomid ODA | N/A | H_10Diese | Cloudy fuel / Water Bottom | no separation | no separation |
| FRF0076 | 75% X-15 / 25% X-102 | 7.3 | H_10Diese | no separation | no separation | 2-phase separation |
| FRF0077 | 50% X-15 / 50% X-114 | 8.9 | H_10Diese | Cloudy fuel / Water Bottom | Clear fuel / Water Bottom | Clear fuel / Water Bottom |
| FRF0091 | 50% X-15 / 50% Tergitol NP-9 | 8.9 | H_30Diese | 3-phase separation | 2-phase separation | 3-phase separation |
| FRF0092 | 50% X-15 / 50% Tergitol NP-9 | 8.9 | API_JP8 | 2-phase separation | 2-phase separation | 2-phase separation |

NOTE: H30_Diesel = ~30% aromatic diesel
H10_Diesel = ~10% aromatic diesel

### 3.4 TEMPERATURE EFFECTS ON EMULSIONS

A series of fuel blends, using the Schercomid ODA surfactant, were prepared to investigate storage stability as affected by temperature. This series of blends included:

3.1 Diesel fuel + 6% surfactant + 10% water. Fuel contained 6% aromatics.

3.2 Diesel fuel + 6% surfactant + 10% water. Fuel contained approximately 30% aromatics.

3.3 JP-8 fuel + 6% surfactant + 10% water. Fuel contained approximately 19% aromatics.

3.4 Synthetic JP-8 + 6% surfactant + 10% water. Fuel contained 0% aromatics.

3.5 50/50 blend of JP-8 and synthetic JP-8 fuels above) + 6% surfactant + 10% water. Fuel contained approximately 9% aromatics.

Samples of each of the blends were prepared and rated visually, and then the following test conditions were established. The samples were inspected visually.

- Test Condition 1: Room ambient, approximately 75°F
- Test Condition 2: 40°F
- Test Condition 3: 125°F

Table 7 is a compilation of the results of the above investigations. In general, temperature effects seem to have occurred during the first several weeks. Therefore, ratings were discontinued after a month or longer without changes being determined.

# Table 7. FRF Storage at Three Temperatures

| Sample ID | Fuel Description | Storage Temp. Code | Date | Rating | Date | Rating | Date | Rating | Date | Rating | Date | Rating | Date | Rating | Date | Rating | Date | Rating | Date | Rating | Date | Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 | AL-27613-FRF DF-2-Dye, 11 April 2007 | 1 | 30-Apr | A | 7-May | A | 14-May | A | 21-May | A | 29-May | A | 4-Jun | A | 11-Jun | A | 18-Jun | A | 25-Jun | A | 2-Jul | A |
| 16 | AL-27613-FRF DF-2-Dye, 11 April 2007 | 2 | 30-Apr | F - 3/16" | 7-May | F - 3/16" | 14-May | F - 3/16" | 21-May | F - 3/16" | 29-May | F - 3/16" | 4-Jun | F - 3/16" | 11-Jun | F - 3/16" | 18-Jun | F - 3/16" | 25-Jun | F - 3/16" | 2-Jul | F - 3/16" |
| 17 | AL-27613-FRF DF-2-Dye 11 April 2007 | 3 | 30-Apr | E - 1/8" | 7-May | E - 1/8" | 14-May | G | 21-May | G | 29-May | F - 1" | 4-Jun | F - 1" | 11-Jun | F - 1-1/2" | 18-Jun | XX | 25-Jun | XX | 2-Jul | XX |
| 18 | AL-27621-FRF DF-2, 11 April 2007 | 1 | 30-Apr | A | 7-May | A | 14-May | A | 21-May | A | 29-May | A | 4-Jun | A | 11-Jun | A | 18-Jun | A | 25-Jun | A | 2-Jul | A |
| 19 | AL-27621-FRF DF-2 11 April 2007 | 2 | 30-Apr | B | 7-May | B | 14-May | B | 21-May | B | 29-May | B | 4-Jun | B | 11-Jun | B | 18-Jun | B | 25-Jun | B | 2-Jul | B |
| 20 | AL-27621-FRF DF-2, 11 April 2007 | 3 | 30-Apr | D | 7-May | D | 14-May | B | 21-May | B | 29-May | F - 3/4" | 4-Jun | F - 1" | 11-Jun | F - 1-1/2" | 18-Jun | XX | 25-Jun | XX | 2-Jul | XX |
| 21 | AL-27074-FRF S-8, 11 April 2007 | 1 | 30-Apr | C | 7-May | C | 14-May | C | 21-May | F | 29-May | F | 4-Jun | F | 11-Jun | F - 2" | 18-Jun | F - 2" | 25-Jun | F - 2" | 2-Jul | F - 2" |
| 22 | AL-27074-FRF S-8, 11 April 2007 | 2 | 30-Apr | C | 7-May | C | 14-May | D | 21-May | D | 29-May | D | 4-Jun | D | 11-Jun | D | 18-Jun | D | 25-Jun | D | 2-Jul | D |
| 23 | AL-27074-FRF S-8, 11 April 2007 | 3 | 30-Apr | A | 7-May | A | 14-May | F - 3/16" | 21-May | F - 1-1/8" | 29-May | F - 2" | 4-Jun | F - 2" | 11-Jun | F - 2" | 18-Jun | XX | 25-Jun | XX | 2-Jul | XX |
| 24 | AL-27618-FRF JP-8 11 April 2007 | 1 | 30-Apr | A | 7-May | A | 14-May | G | 21-May | G | 29-May | G | 4-Jun | G | 11-Jun | G | 18-Jun | G | 25-Jun | G | 2-Jul | G |
| 25 | AL-27618-FRF JP-8, 11 April 2007 | 2 | 30-Apr | A | 7-May | A | 14-May | A | 21-May | A | 29-May | A | 4-Jun | A | 11-Jun | A | 18-Jun | A | 25-Jun | A | 2-Jul | A |
| 26 | AL-27618-FRF JP-8 11 April 2007 | 3 | 30-Apr | D | 7-May | D | 14-May | G | 21-May | G | 29-May | G | 4-Jun | F - 1/2" | 11-Jun | F - 1-1/2" | 18-Jun | XX | 25-Jun | XX | 2-Jul | XX |
| 27 | 50/50 S-8 & FRF JP-8, 12 April 2007 (AL-27618-F & AL-27074F) | 1 | 30-Apr | A | 7-May | A | 14-May | A | 21-May | A | 29-May | A | 4-Jun | A | 11-Jun | A | 18-Jun | A | 25-Jun | A | 2-Jul | A |
| 28 | 50/50 S-8 & FRF JP-8, 12 April 2007 (AL-27618-F & AL-27074F) | 2 | 30-Apr | F - 1" | 7-May | F - 1" | 14-May | F - 1" | 21-May | F - 1" | 29-May | F - 1" | 4-Jun | F - 1" | 11-Jun | F - 1" | 18-Jun | F - 1" | 25-Jun | F - 1" | 2-Jul | F - 1" |
| 29 | 50/50 S-8 & FRF JP-8, 12 April 2007 (AL-27618-F & AL-27074F) | 3 | 30-Apr | A | 7-May | A | 14-May | A | 21-May | G | 29-May | F - 1" | 4-Jun | F - 2" | 11-Jun | F - 2" | 18-Jun | XX | 25-Jun | XX | 2-Jul | XX |

**Storage test installed 26 April 2007 @ 1030 hrs**

**1 = ambient storage**
**2 = 48ºF storage**
**3 = 120ºF storage**

| Storage Rating | Description |
|---|---|
| *A* | clear, no separation |
| *B* | slight haze, no separation |
| *C* | medium haze, no separation |
| *D* | milky, no separation |
| *E* | milky, separation |
| *F* | hazy, separation |
| *G* | clear, slight sediment |

## 3.5 MIST CONTROL ADDITIVE EFFECTIVENESS

Baker Petrolite additive, FLO MXC was selected as a mist control additive. This selection was made based on previous experience with the additive[2]. FLO MXC is reported to be approximately 20–25% polymer in a hydrocarbon solvent. For most testing, we blended 1 ml of FLO MXC into 1 liter of FRF (i.e., approximately 250 ppm polymer). It should be noted that the mist control agent used in the previous work in the 1980s used a polymer added at 0.2% or approximately 2000 ppm[2].

Viscosity (centistokes) measurements were conducted on a DF-2 sample at 40°C to determine the effect of mist control agent on viscosity:

- Sample 1: DF-2 containing 6% surfactant, 10% water: **4.52 cSt**.
- Sample 2: DF-2 containing 6% surfactant, 10% water, 250 ppm mist control agent: **5.13 cSt**.
- Sample 3: DF-2 containing 6% surfactant, 10% water, 125 ppm mist control agent: **4.83 cSt**.
- Sample 4: DF-2 containing 6% surfactant, 10% water, 62.5 ppm mist control agent: **5.39 cSt**.

Kinematic viscosity is very difficult to measure with this polymer in the fuel. The above results are for information only. The results do not follow a consistent pattern based on the level of mist control additive in each sample. We believe this is related to the non-homogeneity of the bulk additive combined with the sensitivity of the viscosity test. It is assumed that the viscosity results for blends made in very large volumes would follow a more regular pattern in that increasing polymer content would increase fuel mixture viscosity.

This data seems to duplicate results of viscoelasticity determinations on AM-1 samples done in the prior program. That data indicated that simple viscosity change was the mechanism affecting mist formation. Ballistic testing, detailed in tests x and y below on the 250 ppm and 125 ppm mist control agent (under same conditions) showed similar results.

## 3.6 Mist Control Degradation Studies

Ballistic testing demonstrated the effectiveness of anti-mist agents (AMA) also known as mist control agents, MCA, blended into FRF formulation. It is known, however, that these mist control agents may also affect the starting of turbine engines due to the low atomization pressure of turbine fuel nozzles.

To determine overall Mist Control Additive (MCA) degradation due to fuel injection system exposure testing was completed in on the in the GEP 6.5L(T) engine, found in the Army's HMMWV and CAT C7, found in the Army's FMTV and STRYKER vehicles engines. JP-8 blends with 125 ppm MCA were supplied directly to the engine, bypassing all ancillary test stand equipment. Fuel samples were collected from the injection system return at idle, peak torque, and rated engines speeds. Laboratory analyses were conducted, using gel permeation chromatography, to determine the molecular weight of the injection system return samples for comparison with values measured from neat drum samples. Results for MCA degradation for the CAT C7 and GEP 6.5L(T) are shown below in Table 8 and Table 9 respectively.

**Table 8. MCA Degradation in CAT C7 Engine**

| CAT C7 | | |
|---|---|---|
| **Sample Location** | **Units [Dalton]** | |
| Drum A Sample | 12.6 | avg |
| Through Lift Pump | 9.0 | avg |
| Engine Return @ Idle (700rpm) | 6.0 | avg |
| Engine Return @ Peak Torque (1400rpm) | 6.6 | avg |
| Engine Return @ Rated Speed (2400rpm) | 5.8 | avg |

**Table 9. MCA Degradation in GEP 6.5L(T) Engine**

| GEP 6.5L(T) | | |
|---|---|---|
| **Sample Location** | **Units [Dalton]** | |
| Drum B Sample | 7.9 | avg |
| Through Lift Pump | 7.5 | single |
| Engine Return @ Idle (750rpm) | 5.3 | avg |
| Engine Return @ Peak Torque (1800rpm) | 5.2 | avg |
| Engine Return @ Rated Speed (3400rpm) | 1.2 | avg |

## 3.7 REDACTED

**Table 10. redacted**

## 3.8 FRF IMPACT ON SMOKE GENERATION

In many tactical vehicles, the onboard propulsion diesel fuel was used to generate obscurant smoke prior to the introduction of JP-8 into the field, this capability was lost when the Army transitioned from diesel fuel to JP-8. As such, the impact of FRF on the ability to generate smoke was looked at as a potential added benefit of the blended fuel. The results of the three base fuels used in the laboratory testing are shown in Table 11. The test results obtained with fog oil, a standard fluid commonly used in the field, were used as the 100% obscuration reference point in this smoke-generation study. Samples 2b, 3b, and 4b were standard FRF blends containing 84% fuel, 6% schercomid surfactant, and 10% water. The results of this study indicated that the addition of these blending components had no significant effect on the obscuration characteristics compared to the neat base fuel, providing no benefit over conventional JP-8. The addition of 125 ppm mist control agent to the standard FRF formulation had a slight negative effect on the obscuration performance of the FRF blend.

**Table 11. Fog Oil Obscuration Testing Results**

| Sample | Flashpoint | Obscuration Rating |
|---|---|---|
| 1. Fog Oil | | 100% |
| 2a. AF-6958 – JP-8<br>2b. AF-6958 – JP-8-FRF<br>2c. AF-6958 – JP-8-FRF+MCA | 41°C | a). 4.4<br>b). 6.8<br>c). 2.8 |
| 3a. AF-7090 – JetA<br>3b. AF-7090 – JetA-FRF<br>3c. AF-7090 – JetA-FRF+MCA | 56°C | a). 5.3<br>b). 4.8<br>c). 3.8 |
| 4a. AF-6795 – Diesel<br>4b. AF-6795 – Diesel-FRF<br>4c. AF-6795 – Diesel-FRF+MCA | 66°C | a). 88.0<br>b). 79.0<br>c). 62.0 |

## 3.9 ATOMIZATION-IGNITION STUDIES (TURBINE ENGINE)

Ballistics testing documented the effectiveness of mist control agents to improve the fire safety of the FRF. Burn time of the FRF following ballistic impact of fuel containing mist control agent was reduced from several seconds to a fireball with a duration of only about one second.

Because of the effectiveness of the mist control agent, we conducted specific studies to evaluate the effect of MCA on atomization in a turbine engine. The concern was based on the viscoelasticity of the fuel containing MCA and the effect on atomization/combustion in the low-pressure air-assist atomizing nozzles used in the M1 Abrams tank. The studies used a T-63 combustor which also has an air assist nozzle. We investigated the atomization characteristics of varying concentrations of MCA. MCA concentrations were selected based on the separate ballistic test results. Samples of sprayed fuel were also collected and analyzed to determine the degree of polymer degradation using the procedure detailed in appendix xxx. A T-63 nozzle was modified as shown in Figure 11.

**Figure 11. Test Rig for T-63 Nozzle**

The modified T-63 air assist nozzle was calibrated according to data previously developed from the T-63 combustor studies[3]. The following data were collected:

- Atomization airflow set at 60 psi.
- Fuel flow reported at 60 lbs/hr to accomplish this fuel flow, with the currently used base fuel, the airflow was determined to require 120 psi air pressure. The airflow required to provide 60 lbs/hr was determined. This testing used 120-psi for all samples.

- Flammability testing was conducted similarly to normal air supply atomization using a high-voltage spark source. All testing was recorded using video.

The following results were recorded based on at least two repeat tests in each case. The ignition source was placed 6 inches from the atomizer.

| Fuel Sample | Test Result |
|---|---|
| 1. JP-8 | Burned |
| 2. JP-8 FRF | Burned |
| 3. JP-8 FRF + 31 ppm MCA | Burned |
| 4. JP-8 FRF + 62 ppm MCA | Burned |
| 5. JP-8 FRF + 94 ppm MCA | Burned |
| 6. JP-8 FRF + 125 ppm MCA | Intermittent |

This testing was to define the maximum amount of mist control agent that would successfully burn in the test apparatus. It should be noted that sample #6 was shown to successfully prevent residual burning, allowing only a small brief fireball during ballistic testing. Additional testing conducted with sample #6 included changing the distance of the ignition source from the standard 6-inch to 3-inch and 12-inch. The results still showed intermittent spray ignition at these other distances.

In a separate set of tests, an AGT-1500 nozzle, previously used in studies during the 1980s, was utilized. The nozzle was thoroughly cleaned and mounted in an enclosure, allowing fuel and air supply controls, as shown in Figure 12 - Figure 14. Based on information taken from the report, "*Evaluation of Fire Resistant Fuel in the AGT-1500 Gas Turbine Engine*" (March 1988, Textron Lycoming), a series of fuel-air flow calibrations were conducted. Figure 15 is an air-fuel flow calibration showing proper nozzle performance.

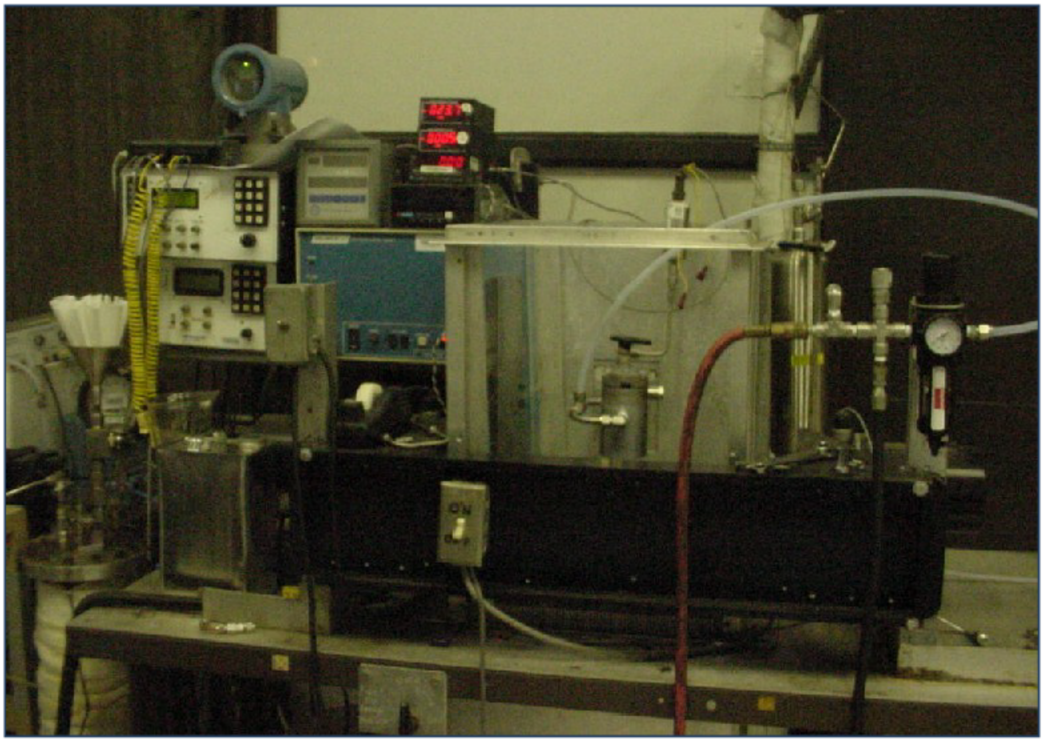


**Figure 12. AGT-1500 Mini Com Fuel Calibration Laboratory**

**Figure 13. AGT-1500 Mini Com Mounted in Fire Test Laboratory**

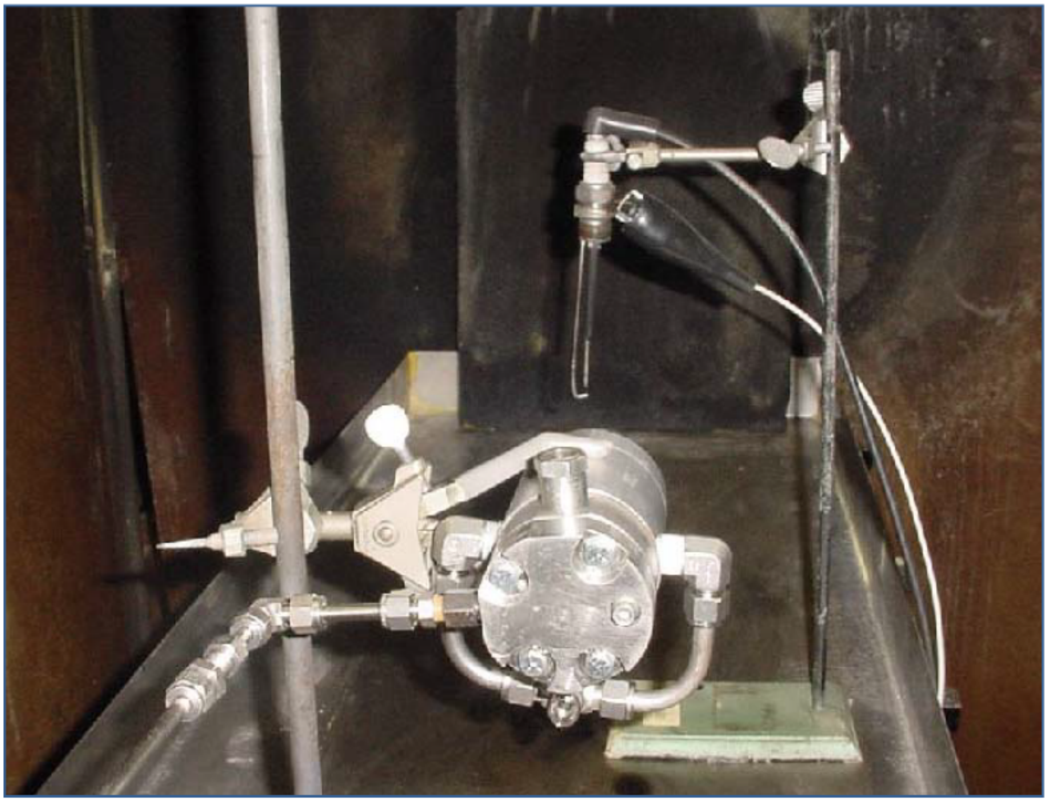


Figure 14. AGT-1500 Mini Com Showing Ignition Source

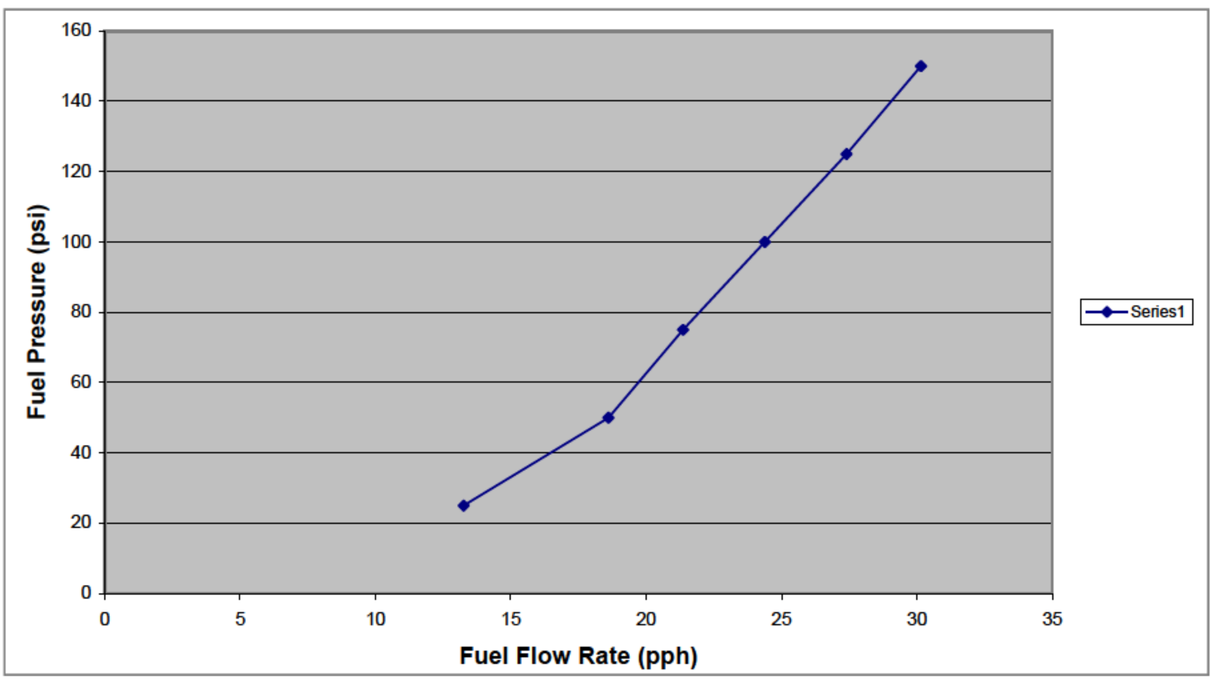



Figure 15. AGT-1500 Mini Com Pilot Swirl Pressure Atomizer (Primary Starting Atomizer)

The AGT-1500 uses a pressure swirl atomizer for starting and a secondary air-assist atomizer for full scale running. We calibrated the nozzle under start-up conditions (fuel flow and atomizing pressure). Two different experiments on the AGT-1500 mini-com were conducted: 1) determine the ability of the engine to start using fuels containing MCA additives, and 2) the polymer shear that occurs when the nozzle is at start-up conditions. Results of the spray-ignition testing of the JP-8/MCA samples are listed below:

- Sample 1: JP-8–Ignition with full flame development
- Sample 2: JP-8 FRF–Ignition with full flame development
- Sample 3: JP-8 FRF with 31.25 ppm MCA–Ignition with full flame development
- Sample 4: JP-8 FRF with 62.5 ppm MCA–Ignition with reduced flame development
- Sample 5: JP-8 FRF with 93 ppm MCA–Ignition with intermittent flame development
- Sample 6: JP-8 FRF with 125 ppm MCA–Intermittent ignition

The test results from the T-63 air assist nozzle and the AGT-1500 indicate that 125 ppm MCA is at the far edge of acceptable MCA additive present in the fuel while still allowing ignition of the fuel in a turbine engine.

### 3.10 FUEL Flammability BENCH TESTS

TFLRF investigated whether flame propagation testing and other fuel properties can be used to predict FRF effectiveness against ballistic threats. The results of these tests are presented in "Correlation Of Laboratory Flame Propagation Testing Results With Ballistic Testing Utilizing Several Threats With Varying Explosive."[4] A summary is given below.

The results of the chemical analysis, for the fuels selected at random, did not show a tight correlation with flame propagation results as presented in Table 12. However, as a general rule, flashpoint seemed to be the controlling factor in flame propagation.

While aromatic content may be a factor in distillation and flashpoint, our data indicated that higher aromatics did not always correlate with flame propagation. For example, one sample had 20.1% aromatics, a flash point of 48.5°C, and a higher propagation rate than another sample with a flash point of 50.5°C and aromatic content of 8.6%.

**Table 12. Flame Propagation Testing of Several Reference Fuels**

| FLAME PROPAGATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | TIME TO PROPAGATE | PROPAGATION | |
| CAN# | REF | FLASH PT | CL# | AROMATICS | FBP °C (1) | IN SECONDS (2) | TIME IN SECONDS (3) | PROPOGATION RATE. INCH/SEC (4) |
| 1 | | 56.5 | 09-0207 (JP-8) | 16.8 | 272 | 10.62 | 11.45 | 3.06 |
| 4 | | 59.5 | 09-0210 (Jet A) | 18.7 | 287 | 4.8 | 10.5 | 3.33 |
| 5 | | 48.5 | 09-0211 (JP-8) | 20.1 | 304 | 2.34 | 6.61 | 5.3 |
| 2 | | 50.5 | 09-0208 (JP-8) | 8.6 | 289 | <1 | 1.1 | 31.82 |
| 3 | | 67.5 | 09-0209 (ULSD) | 21.4 | 382 | 120 | 21.8 | 1.61 |
| 6 | | 82 | 09-0212 (Diesel, Special Test Fuel) | 35.7 | 398 | >10 | No Propagation | No Propagation |
| 7 | | 39 | 09-0213 (Jet A) | 16.6 | 292 | <.1 | <1 | >35.0 |
| 8 | | 56 | 09-0214 (Jet A) | 20.5 | 303 | 7.4 | 10.98 | 3.19 |
| 9 | | 65 | 09-0215 (ULSD) | 19.5 | 418 | >10 | No Propagation | No Propagation |
| 10 | | 40 | 09-0216 (Jet A) | 18.3 | 345 | 0.62 | 1.49 | 23.49 |
| 11 | | 91 | 09-0217 (Diesel Fuel) | 20.8 | 412 | Wick Wouldn't Stay Lit Even After 3 Tries | | |
| 12 | | 46 | 09-0218 (Jet A) | 15 | 270 | 0.39 | 0.3 | 116.67 |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| (1) Final Boiling Point | | | | | | | | |
| (2) Time to Propagate after Wick was Ignited | | | | | | | | |
| (3) Time to Propagate Length Trough | | | | | | | | |
| (4) Propagation Rate Calculated | | | | | | | | |

Laboratory analysis, flame propagation, and ballistic testing of several reference fuels was completed for comparison purposes. Full-scale ballistic tests (using 2.5" VIPER shaped charge) were conducted on the same three blends of fuel as those tested in the laboratory testing above. The fuel blends tested are listed below:

- JP-8 Base Fuel (Fuel #1), JP-8 FRF (Fuel #2), and JP-8 FRF+125 MCA (Fuel #3). Figure 16 depicts each of these tests.
- Jet A Base Fuel (Fuel #4), Jet A FRF (Fuel #5), and Jet A FRF+125 MCA (Fuel #6). Figure 17 depicts each of these tests.

- Diesel Base Fuel (Fuel #7), Diesel Fuel FRF (Fuel #8), and Diesel Fuel FRF+125 MCA (Fuel #9). Figure 18 depicts each of these tests.

Figure 16 - Figure 18 show the estimation of the ballistic flame propagation timing, that is presented in Table 12.

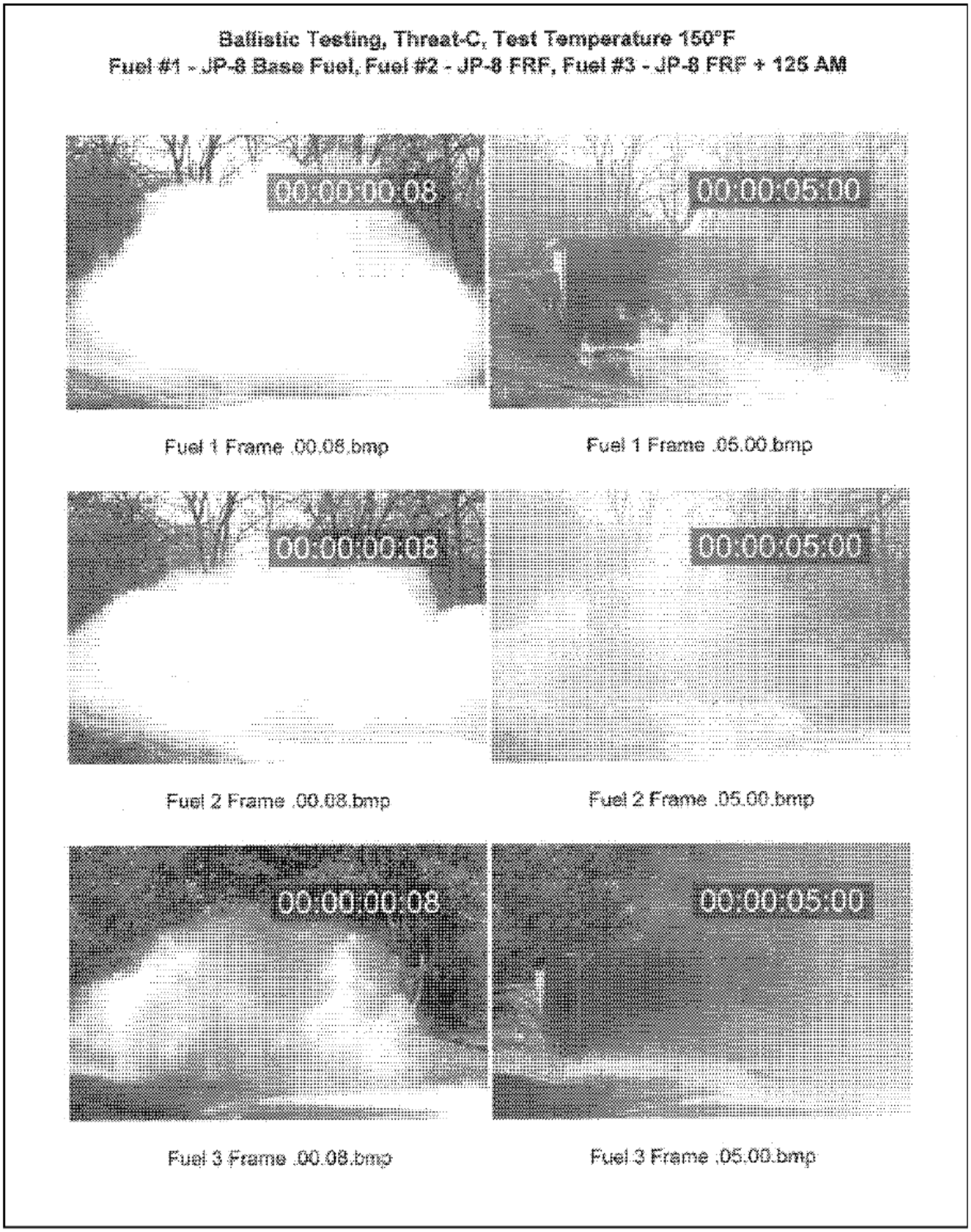



**Figure 16. JP-8 Base Fuel, JP-8 FRF, and JP-8 FRF+125 Anti Mist Additive**

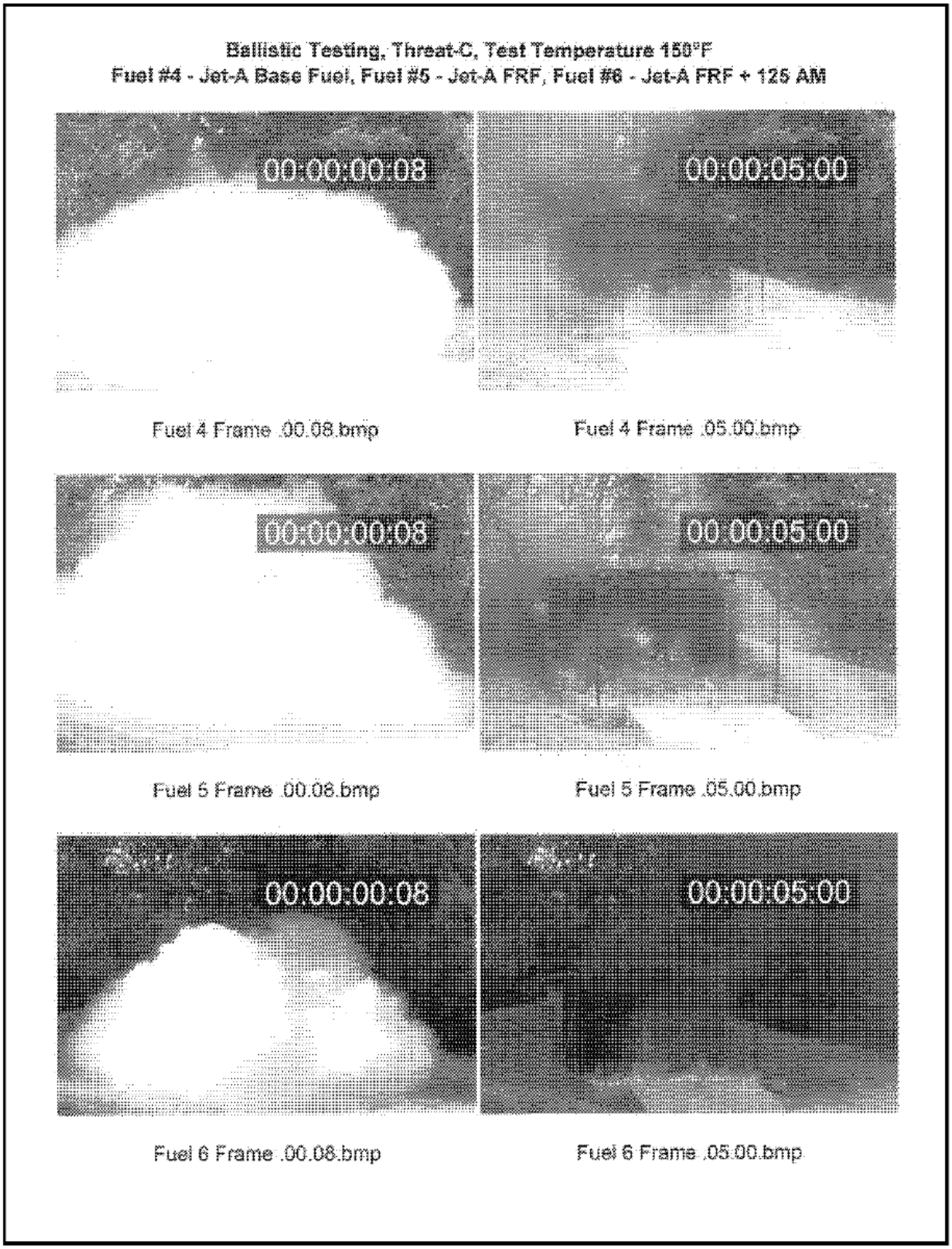



**Figure 17. Jet A Base Fuel, Jet-A FRF, and Jet-A FRF+125 Anti Mist Additive**

**Ballistic Testing, Threat-C, Test Temperature 150°F**
**Fuel #7 - Diesel Base Fuel, Fuel #8 - Diesel Fuel FRF, Fuel #9 - Diesel Fuel FRF + 125 AM**


Fuel 7 Frame .00.08.bmp

Fuel 7 Frame .05.00.bmp

Fuel 8 Frame .00.08.bmp

Fuel 8 Frame .05.00.bmp

Fuel 9 Frame .00.08.bmp

Fuel 9 Frame .04.14.bmp

**Figure 18. Diesel Base Fuel, Diesel Fuel FRF, and Diesel Fuel FRF+125 Anti Mist Additive**

Flame propagation testing of several reference fuels was completed, as shown in Table 13. This data was analyzed and compared to data of currently used fuel blends, i.e., base fuel, FRF 10% $H_2O$ blend, and FRF 10% $H_2O$ blend + 250 ppm MCA.

**Table 13. Flame Propagation of Blended Fuels at 66°C (150°F) Test Temperature using Viper Shape Charge Vs. Laboratory Fixture**

| Test Sample | Ref. Fuel | Flash Point °C | % Aromatics by D1319 | Test Fixture Time to Propagation, sec | Test Fixture Propagation Rate, in/sec | Threat-C Time to Propagation, sec | Threat-C Propagation Rate in/sec, *(Approx*)* |
|---|---|---|---|---|---|---|---|
| JP-8 | 1 | 41 | 17.9 | 1 | >35 | <2.5 | 60* |
| JP-8 | 2 | | | 1.9 | 18.4 | <2.5 | 60 |
| JP-8 | 3 | | | <1 | >35 | <2.5 | 60 |
| Jet-A | 4 | 49 | 18.6 | 11 | 3.2 | <2.5 | 60 |
| Jet-A | 5 | | | 39 | .89 | <2.5 | 60 |
| Jet-A | 6 | | | 21 | 1.6 | <2.5 | 60 |
| Diesel Fuel-2 | 7 | 66 | 19.7 | DNP | N/A | <2.5 | N/A |
| Diesel Fuel-2 | 8 | | | DNP | N/A | <2.5 | N/A |
| Diesel Fuel-2 | 9 | | | DNP | N/A | <2.5 | N/A |

The results in the ballistic testing correlated well with the laboratory testing of the analogous blends are shown in Table 12. There was some variation in time due to the energy ratio of wick ignition compared with vs. ballistic ignition and the residual burning (rate of flame spread) varied, based on flashpoint. There was no perceived marangoni effect. The marangoni effect is an enhancement of flame propagation due to heat transfer to fluid surface ahead of flame. That effect was expected due to changes in propagation rate of fuels containing the viscoelastic polymer. It appears that the laboratory procedure is worthwhile in providing a measure of flame propagation at various fuel temperatures.

## 3.11 BLENDING SYSTEM DESIGN

The overall requirements for this task were to:

- In conjunction with Army logisticians, develop a plan for the introduction of one to three FRF blending systems.
- Develop a FRF blending system preliminary design that maximizes the use of existing Army petroleum and water handling equipment already available in the Army inventory, identify additional components as needed, and develop a time and procurement cost estimate for constructing one to three such units.
- Identify requirements of the FRF blending system with enough detail to allow the preparation of a procurement package. The requirements shall include training needs.

Through discussions with the Army, clarifications to the design requirements evolved. In particular, logistic interface requirements and level of involvement with procurement packages were modified. Under the modified requirements, a "technology demonstrator" would be fielded, with the purpose of gaining field use and operational experience. In order to streamline this process, for the requirement to interface with Army logistical activities was removed. Emphasis could then be placed on design concept evaluations under field conditions. As such, efforts focused on the development of a preliminary design for a technology demonstrator. A Legacy Blender, developed under a previous program, was found capable of producing sufficient volumes of FRF. This unit served as a laboratory test bed for developing design data.

### 3.11.1 Water Purification

Based on conversations with Dr. Jay Dusenbury (TARDEC), a review of FM 10-52, FM 10-52-1 and other relevant publications, Army water-treatment assets were identified. These assets are typically deployed during field operations. Important characteristics of these assets (such as water throughput rate, conduit size, discharge pressure, and approximate size and weight) were reviewed for possible integration of these assets into a fuel blending and dispensing station.

Items in the Army inventory that were considered the design of a blending system included the following:

- Reverse Osmosis Water Purification Unit (ROWPU); 600 gallons per hour
- Reverse Osmosis Water Purification Unit (ROWPU); 3000 gallons per hour
- Reverse Osmosis Water Purification Unit (ROWPU); 150,000 gallons per day
- Tactical Water Distribution System (TWDS); 600,000 gallons of water per day
- Forward Area Water Point Supply System (FAWPSS)
- Semi trailer Mounted Fabric Tank (SMFT)
- Assortment of 125, 250, and 600 gallon per minute pumps (fuel and water)

Included in the above are numerous; fitting sizes and types, collapsible bags, and numerous ancillary components. Also, if one includes fuel terminal operations, the Inland Petroleum Distribution System (IPDS), and the blending components developed by Hammonds, then the assets available to use are plentiful. The challenge was to develop a blending system design that makes effective use of the assets.

Initially, the most likely location for an FRF blending/dispensing station was judged to be the most forward point of a fuel distribution system. However, other locations and fueling/blending scenarios were also considered. One key consideration was the need for potable water for FRF blending. Since a Reverse Osmosis Water Purification Unit (ROWPU) will always be available for any planned field operation, it is highly improbable that water needed for the FRF will be pumped directly from an indigenous source (rivers, lakes, municipal sources) without first being processed by a ROWPU. The ROWPU is 99 percent efficient in removing unwanted contaminants from non-potable water. Separate investigations of required water quality found that water with up to 1000 ppm dissolved solids is acceptable, with special additives (see additional information on water quality in Section 3 of this report).

### 3.11.2 Mixers and Mixing

***<u>Technology Demonstrator Blending Unit</u>***

For the design of a technology demonstrator, the minimum requirement was set as the ability to fuel a HMMWV in approximately 2 minutes. The HMMWV has a 25-gallon tank so 12.5 GPM (750 gallons per hour) flow was required. We designated this unit FRF-TD-750. Note that the flow rate of the technology demonstrator was 7.5 times higher than the previously mentioned legacy blender unit. (For reference, the HEMTT-LHS has a 155-gallon tank, which may set the sizing of larger technology demonstrators.) Assuming a ratio of 84/10/6 of fuel/water/surfactant, the fuel pump, water pump, and surfactant pump are respectively sized for 10.5, 1.25, and 0.75 GPM. Further, the technology demonstrator services 12 vehicles per hour (one every five minutes), which would mean the hourly consumption of fuel, water, and surfactant would be 252, 30, and 18 gallons. These relatively small volumes leave one with numerous options for liquid storage, especially if fuel is available in an adjacent fuel bladder within a terminal. Design concepts for a skid mounted technology demonstrator were developed based on the general flow requirements provided above.

Blending energy, efficiency, and effectiveness are important trade-off parameters for characterizing designs for blending units. For example, it is fairly well established that the formation of a given emulsion requires a certain amount, depending on the fluids, of fluid shear (forced relative motion between the fuel and water fractions) over some given time span. Emulsifiers enhance the ease by which emulsions form, but nonetheless, a tradeoff between mixing approaches (shearing) and the quantity of emulsifier required is needed to arrive at reasonable and cost effective designs for blenders.

Additive injection equipment used for jet fuel / additive blending, produced by Hammonds (Model 4T-4A1 tactical JP-8 injector), represents the only current Army inventory item that is potentially useful for blending FRF. This is a relatively small sized piece of equipment. We judged that it would likely work fine for injecting water into fuel, but further mixing would be required to form an emulsion with the desired characteristics.

Viable blend system designs were investigated through reviews of numerous patents, commercial product literature, and open technical literature. From these reviews, several mixing techniques were identified along with various analysis methods that would enhance and shorten the design process. Several laboratory scale mixers were investigated to help quantify the effectiveness of the mixing methods.

As part of the system design effort, a plan for deploying a "mixing/blending" system was completed. The plan's objective was to define a practical means for deploying a small scale mixing unit that would essentially operate as a stand-alone demonstrator unit. A good candidate deployment method was to incorporate a small blending unit on a skid that also contains tanks (water and emulsifier). This skid would be trailer mountable to increase modularity, mobility, and ease of deployment to selected locations.

Configuration and spatial layout of components needed for a technology demonstrator were defined. Three possible sizes of a technology demonstrator capable of refueling a HMWWV or HEMTT in a reasonable time are shown in Table 14. Several assumptions are built into this table. Firstly, the fuel tank sizes used for the HMWWV and HEMTT are 25 and 155 gallons respectively. It was further assumed that the time between the capping off one vehicle and the initiation of fueling the next vehicle is one minute. Based on these assumptions the FRF-TD-750 can fill 20 HMWWV's per hour, the FRF-TD-3000 can service 14.6 HEMTT's per hour. Most likely these rates would not be realized because one would need a continuous line of vehicles ready for servicing.

**Table 14. Sizing of Technology Demonstrators**

| Model* | *GPM* | Nozz. Dia. | Fueling Application | Fill Time (min.) | Vehicles/ Hr | Total Consumption per Hour (Gallons) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Fuel | Water | Surfac. | Total |
| FRF-TD-750 | 12.5 | 0.75 | HMWWV's (20/hr) | 2 | 20 | 420 | 50 | 30 | 500 |
| FRF-TD-1500 | 25 | 1 | HEMTT-LHS (8.3/hr) | 6.2 | 8.3 | 1080.66 | 128.65 | 77.19 | 1286.5 |
| FRF-TD-3000 | 50 | 1.5 | HEMTT-LHS (14.6/hr) | 3.1 | 14.6 | 1900.92 | 226.3 | 135.78 | 2263 |
| *FRF-TD-XXXX; XXXX = Maximum Continuous Flow Rate in Gal/hr. | | | | | | Mixture Ratio | | | |
| | | | | | | 0.84 | 0.1 | 0.06 | |

Various configurations of the pumping and mixing equipment were possible; however, the use of a dedicated pump per fluid (water, fuel, and surfactant) that forces each fluid through a static mixer was found to be the preferred arrangement. This arrangement was proven successful with the legacy system. So to minimize development risk the technology demonstrator was based on this arrangement. The implicit assumption with this arrangement was that FRF would be blended on an as needed basis. There would be no need for a batch operation, although the FRF could be produced and stored in other containment.

The line sizing was based on an electrostatics criterion where, as a general rule of thumb, velocities should be kept below 3 m/s (~10 ft/s). This velocity range was also favorable from a pressure drop point of view because the pressure drop per foot of tubing or piping would be low. Sizing of the fuel, water, and surfactant pumps was governed by a fixed ratio of 84/10/6 for the fuel, water, and surfactant, although allowances for variations of these ratios could be easily accommodated.

Tank sizing information was inferred from Table 14 as well as a framework for footprint sizes of various components suitable for installation on a skid system. For example, the –3000 model includes a 226-gallon water from which plausible dimensions of a flat head tank are likely to be 40 inches in diameter by 41.5 inches tall with inlet and outlet nozzles that are 1.5 inches in diameter.

Pumping power requirements for the –750, –1500, and –3000 models can be estimated based on an assumed system pressure drop of approximately 75 psi. Power estimates were 0.9, 1.8, and 3.6 hp for the three models operating with 60% power conversion efficiency. While these pumping power requirements were very modest, additional power would be required on the skid to run ancillary equipment and electronics.

Power source and power distribution options that were considered included; (1) an Internal Combustion (IC) engine driving an electrical generator that supplies electrical energy to electric pump motors, (2) an IC engine driving a hydraulic pump to supply hydraulic power to hydraulic

pump motors, and (3) an option to pull electrical power from an indigenous source or an existing electrical power generator or from the electrical power take-off on many military vehicles. Also, considered was a combination of power sources (onboard IC engine and provision for external electrical power).

The skid structure size was governed by onboard tank size and the weight of the stored fluids and provisions for mechanical/electrical equipment (fuel pre-filters, valves, flow meters, controls, etc.). Onboard tanks for the unblended fuel (JP-8 or diesel) were not included on the skid as it was assumed that JP-8 or diesel would be available from other sources and there would be no need to carry fuel except that which would be needed for an onboard IC engine. A design goal was to size the skid(s) such that it would fit within the floor space of Tricon Container (~6′-4″ x 7′-6″), because the Tricon would provide a simplified method for transport.

Based on the general system requirements developed previously, a concept layout was developed for a technology demonstrator blending unit that would be capable of servicing 20 HMWWV's per Figure 19. Technology Demonstrator Blending Unit Concept Layout. Based on a concept sketch for the -750 model, a listing of components, which continued to evolve as the design proceeded forward, is shown in Table 15.

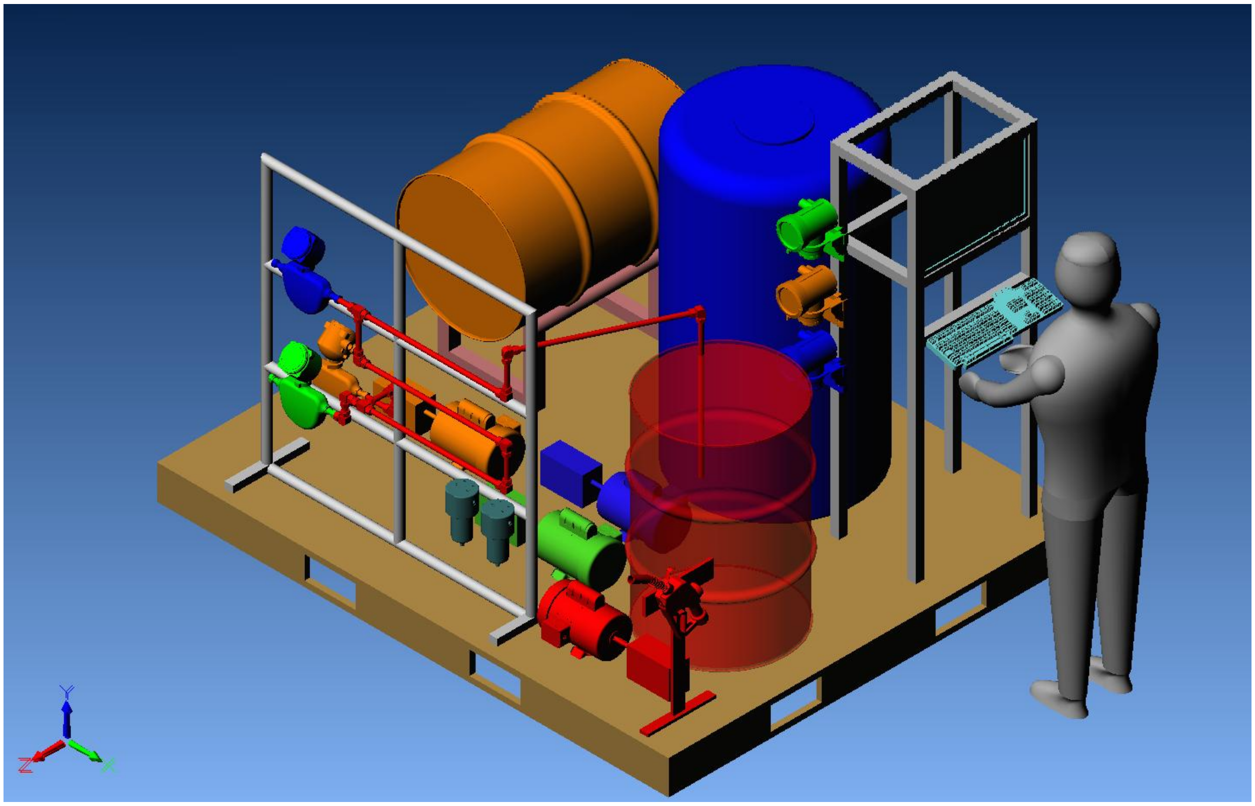


**Figure 19. Technology Demonstrator Blending Unit Concept Layout**

**Table 15. Components for a Technology Demonstrator Unit for Blending Fire Resistant Fuels**

| Item No | Part No | Description | Amt Rqd (ft, no,etc) | Unit Wt. (lbs) | Sub. Tot. (lbs) | Item Wt. (lbs) |
|---|---|---|---|---|---|---|
| 001 | TD-750-001 | ***Skid Assembly - 001*** | | | | 520.11 |
| | TD-750-001-001 | 6x2 Channel Iron, 10.5  bs/ft | 12 | 10.5 | 126 | |
| | TD-750-001-002 | 6x4 box beam-3/8"wall, 22.37 lbs/ft | 6 | 22.37 | 134.22 | |
| | TD-750-001-003 | 1/4" deck plate 3'-6 x 6' 10.21 lbs/ft2 | 21 | 10.2083 | 214.37 | |
| | TD-750-001-004 | 2'X3/16" 1.27 lbs/ft (spill containment) | 20 | 1.276 | 25.52 | |
| | TD-750-001-005 | weld rod | 1 | 20 | 20.00 | |
| 002 | TD-750-002 | ***Liquid Storage - 002*** | | | | 125.00 |
| | TD-750-002-001 | 50 gal Water Storage Tank 38x19x20 | 1 | 83 | 83.00 | |
| | TD-750-002-002 | 45 gal Surfactant Tank, | 1 | 22 | 22.00 | |
| | TD-750-002-003 | Hold down strap | 2 | 5 | 10.00 | |
| | TD-750-002-004 | Hold down strap | 2 | 5 | 10.00 | |
| | TD-750-002-005 | Tank fittings | | | | |
| 003 | TD-750-003 | ***Piping and Pumps - 003*** | | | | 179.9 |
| | TD-750-003-001 | Fuel Pump with Motor | 1 | 39 | 39 | |
| | TD-750-003-002 | Surfactant Pump with Motor | 1 | 35 | 35 | |
| | TD-750-003-003 | Water Pump with Motor | 1 | 37 | 37 | |
| | TD-750-003-004 | 3/4" SS Tubing x 0.49 wall, 0.37 lb/ft | 20 | 0.37 | 7.4 | |
| | TD-750-003-005 | 3/4" ball valves | 9 | 2 | 18 | |
| | TD-750-003-006 | 3/4" Check valves | 3 | 2.5 | 7.5 | |
| | TD-750-003-007 | 1/2" drain valves | 3 | 1 | 3 | |
| | TD-750-003-008 | Misc Fittings, Lot | 1 | 15 | 15 | |
| | TD-750-003-009 | Fuel Inlet Fitting | 1 | 3 | 3 | |
| | TD-750-003-010 | Static Mixer | 3 | 5 | 15 | |
| | | ***Power Distribution - 004*** | | | | |
| 004 | TD-750-004 | | | | | 224.4 |
| | TD-750-004-001 | NEMA 4X Enclosures(10x8x6) | 3 | 4.8 | 14.4 | |
| | TD-750-004-002 | Conduit, 0.5  b/ft | 20 | 0.5 | 10 | |
| | TD-750-004-003 | 2.5 kW Genset | 1 | 200 | 200 | |
| 005 | TD-750-005 | ***Dispensing - 005*** | | | | 148 |
| | TD-750-005-001 | Metering Unit | 1 | 25 | 25 | |
| | TD-750-005-002 | Strainer | 2 | 20 | 40 | |
| | TD-750-005-003 | 50 gal buffer tank for mixed product | 1 | 83 | 83 | |
| 006 | TD-750-006 | ***Controls - 006*** | | | | 32 |
| | TD-750-006-001 | Fuel flow meter | 1 | 7 | 7 | |
| | TD-750-006-002 | Surfactant flow meter | 1 | 5 | 5 | |
| | TD-750-006-003 | Water flow meter | 1 | 5 | 5 | |
| | TD-750-006-004 | Microprocessor Control Unit | 1 | 10 | 10 | |
| | TD-750-006-005 | Pressure Sensors | 3 | 1 | 3 | |
| | TD-750-006-006 | Limit Switches | 4 | 0.5 | 2 | |
| | TD-750-006-007 | | | | | |
| 007 | TD-750-007 | ***Miscellaneous - 007*** | | | | 75 |
| | TD-750-007-001 | Lighting, one night lamp | 1 | 5 | 5 | |
| | TD-750-007-002 | Tool box | 2 | 15 | 30 | |
| | TD-750-007-003 | Adapter Kit (connectors for liquids) | 1 | 15 | 15 | |
| | TD-750-007-004 | Mechanical Hardware | 1 | 25 | 25 | |
| | | | ***Estimated Weight (dry)*** | | | 1304.41 |

One design goal was to size the -750 model such that two units could fit on the floor space of one shipping Tricon. This would require a skid to fit within a space approximately 3½′ × 6′. Approximately 7′ in the vertical dimension were available, which allowed considerable design flexibility for designing a -750 unit to fit within the available volume. The -750 model was fitted with a 50 gallon water tank (38″×19″×20″ tall) made of polyethylene with metal tie down straps. A similar, but smaller, tank for the surfactant was also attached to a skid structure. These tanks take up about 1/2 of the available skid area; however, sufficient floor space for the pumps remained. Provisions were made for connecting the unit to a fuel supply source such as those found at a tactical petroleum terminal; and, adapter kits were provided for connecting to alternative sources.

For the −750 unit, the most practical power option was a small 2.5 to 3 kW generator set, driven by a small IC engine capable of running on kerosene type fuels. An option to pull electrical power from an indigenous source or from the electrical power take-off on many military vehicles was included in the design. Electrical distribution in general followed applicable codes that generally require sealed distribution panels, enclosed cabling, strain relief, NEMA enclosures, etc.

The blending control strategy significantly impacts the power distribution strategy. The basic control methods included; (1) variable speed electrical pumps, (2) fixed speed electrical pumps with bypass control, (3) hydrostatic drives that control pump delivery characteristics, and (4) pumps that are mechanically connected to produce a particular mixture ratio. These control methods were implemented to provide the proper amounts of surfactant to be mixed with the fuel and the proper amount of water to be mixed with the fuel-surfactant blend. The actual mixing of the fluids was accomplished with a static mixer.

Ancillary items included fuel filters, lighting, lifting lugs, and storage boxes for tools and spare parts. The skid structure incorporated lifting pockets suitable for forklift operations.

The layouts (see Figure 20) for the FRF-TD-750 showed that the blending unit could be contained on a platform with dimensions of 42″ x 72″ inches. For this particular unit, a small generator set was included on the platform, thus relieving the need to hook up a separate electrical power unit. For ease of shipping and possible containment in the field, the entire –750 unit, including tanks for limited amounts of water and surfactant, fit into a single Tricon.

The –1500 model was specified to deliver twice the flow rate of the –750 model. The-1500 model would be more suitable for fueling a HEMTT-LHS or PLS because of their fuel tank size (105 gallons). This particular unit could fuel eight or more HEMTT's per hour. At a fuel rate of eight per hour, approximately 1080 gallons of fuel, 128 gallon of water, and 77 gallons of surfactant would be consumed. Tanks sized for 128 gallons and 77 gallons were the primary factors controlling the platform area and volume of the –1500 blending unit. While detailed weight estimates were not computed, it was estimated that the –1500 unit would be in the range of 1600 to 1800 pounds. This was based on a dry weight of the –750 unit of approximately 1400 lbs. The basic components for the –1500 unit were only slightly larger than the –750 unit except for the physical space of the tanks. Line sizes were 1 inch diameter as compared to ¾ inch found on the –750. The physical sizes of the pumps were only slightly larger and the majority of the remaining equipment (electronics, mechanical fittings, etc.) was about the same size. Hence, the preliminary indications were that the – 1500 unit would fit into a Tricon as did the –750 unit, however installation of the larger tanks could be a challenge to fit within the Tricon volume.

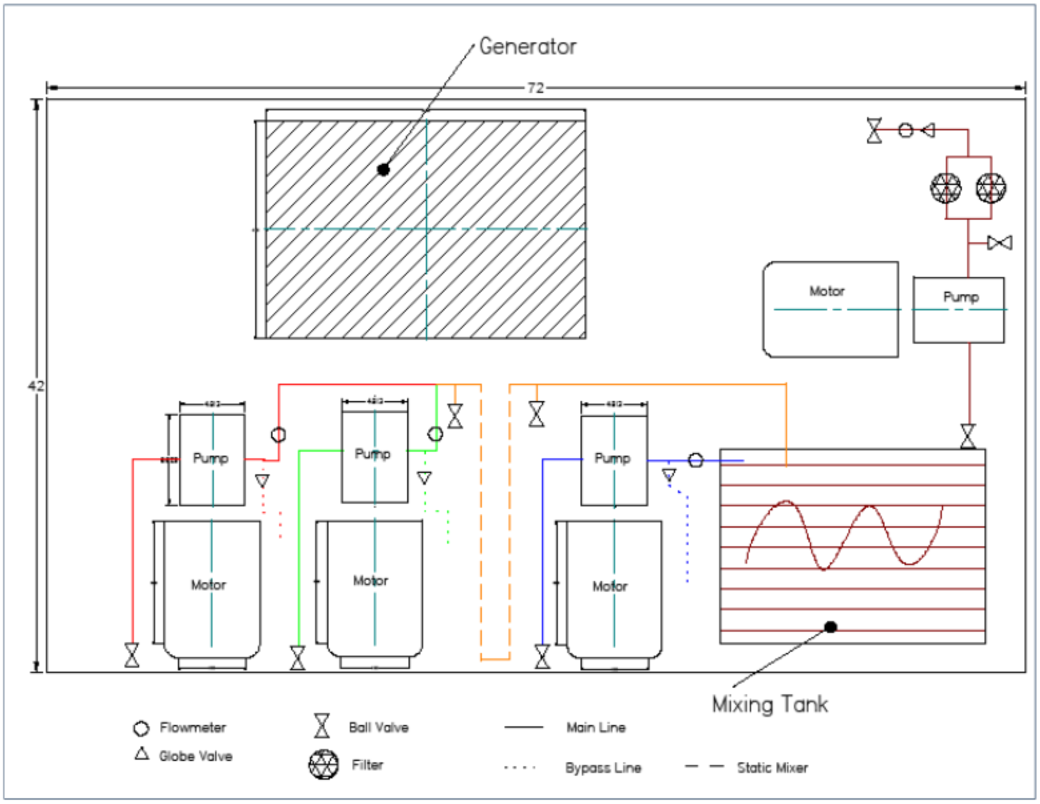



**Figure 20. Three Pump Configuration (Blend on Demand)**

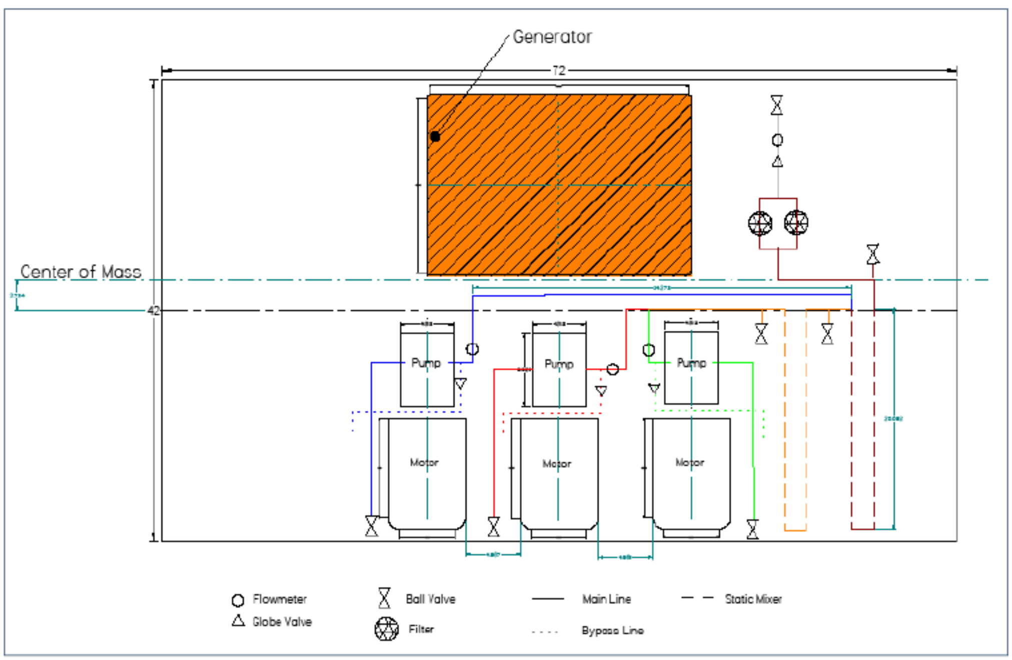



**Figure 21. Semi-Batch Configuration (Pump from Mixing Tank)**

Based on a strategy to field a reasonable sized unit, more emphasis was placed on the smaller demonstrator that could deliver 750 gallons per hour of blended fuel mixed with JP-8 as a feedstock rather than only diesel fuel. The selection of mixing elements with specific performance directed toward JP-8 was therefore narrowed. A majority of the design (pumps, piping, instrumentation and control, safety, etc.) was somewhat independent of the exact formulation of the FRF with the exception of the mixers.

***On-Demand Blending Unit***

An on-demand unit with a real-time mixing, was also devised. The basic difference between this unit and the batch-processing unit was that there was no on-board storage of fuel. The on-demand unit mixes on the fly where there are indigenous supplies of fuel and water. If surfactant or anti-misting agents are not available at the blending site, then small volume storage tanks would be required to contain these agents. Fortunately the volume is relatively low, approximately 30 gallons. These small tanks are not shown in either design (Figure 22 and Figure 23). A unit footprint of 72 inches by 42 inches can be maintained for the –750 units so they will fit into a TRICON.

The on demand unit has three pumps; one for fuel; one for surfactant, and one for water. Lifting slots are provided for forklift operations. The two tall containers are filter/strainer units. Piping layout details are not shown. This particular unit incorporates its own generator set for providing power to the electric pump motors.

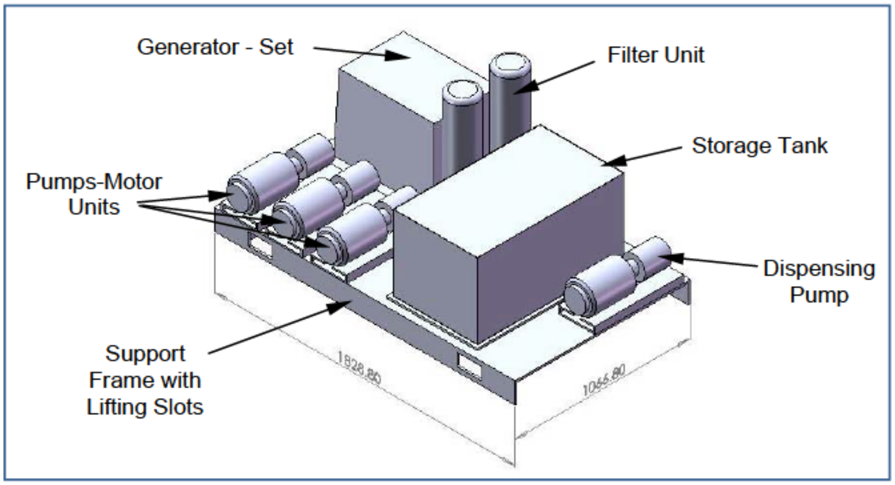



**Figure 22. Three Dimensional Layout of a 750 Gallon per Hour "Batch-Mode" Blending Unit**

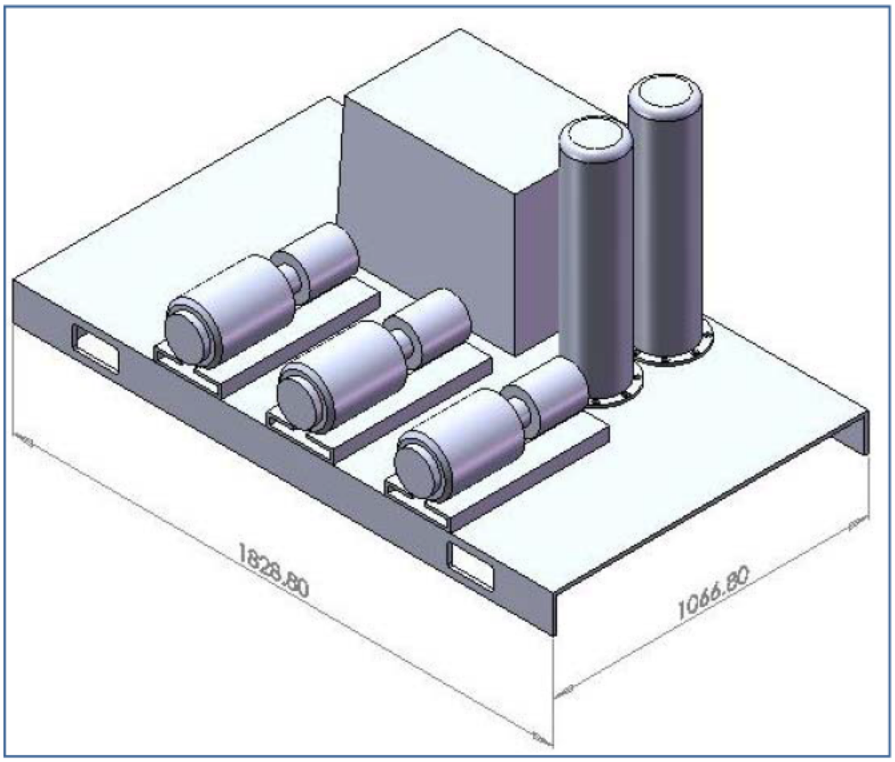



**Figure 23. Three Dimensional Layout of a 750 Gallon per Hour "On-Demand" Blending Unit**

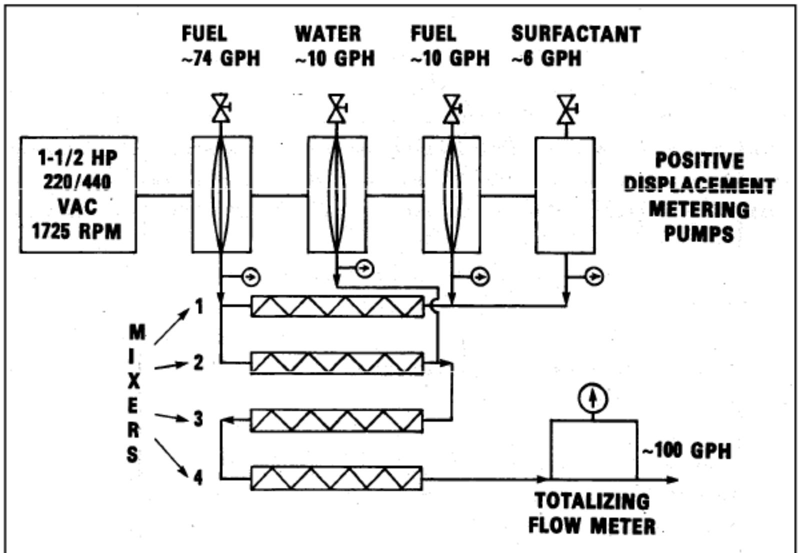
### 3.11.3 Ultrasonic Probe Blending

We created a limited number of blends using an ultrasonic probe. It was thought that the additional energy imparted on the blend might speed and improve the emulsification process. Generally, the emulsions prepared using the Schercomid ODA with either diesel or JP-8 were successful. Clarification of the blend was achieved in less than 3 minutes using the ultrasonic probe. Other surfactants that were previously successful by conventional stirring methods were less successful and resulted in milky solutions. Our mixing procedure for these experiments was likely the cause—the water was added as a slug before ultrasonication began. This caused an immediate increase in solution viscosity that even the ultrasonic probe could not overcome.

One disadvantage to using the ultrasonic probe in static blends is the heat generated by the probe. If blending beyond 5 minutes was necessary, then cooling of the sample would be required. This would probably not be an issue in an on-line system because the fuel would dissipate the heat generated by the probe.

## 3.12 LEGACY BLENDER INVESTIGATIONS

As part of the study to determine the blending energy required to form a stable microemulsion, the 4-stage blender developed for the previous study in the 1980s was refurbished. This unit (Figure 24 and Figure 25) also provided fuel for the extended engine tests conducted later in the program. This unit's shear energy (mixing) was provided using Kenics static mixers.




First Stage: The surfactant (6 vol%) is preblended with diesel fuel (approximately 12 vol% of fuel) through a 32-element Kenics® mixer.

Second Stage: This preblend of fuel and surfactant is blended with the remaining fuel (72 vol%) through another 32-element Kenics mixer.

Third Stage: The fuel-surfactant blend is then blended with water (10 vol%) through two 32-element Kenics mixers in series.

**Figure 24. Schematic Flow Diagram -100 gal/hr FRF Blending System**

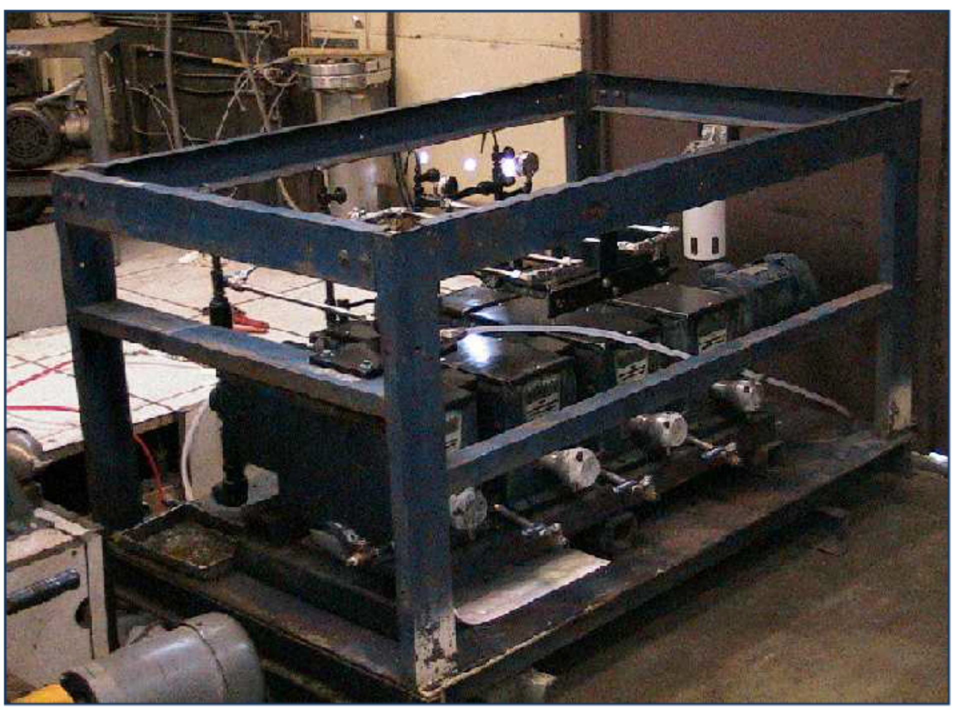


**Figure 25. Legacy FRF Blender**

The legacy FRF blender was refurbished and slightly modified (see Figure 26). The modified unit mixed the surfactant immediately with the main fuel stream and thus only three pumps were used instead of the original four. (The original unit mixed fuel and surfactant and then injected this mix into the main fuel stream.) The performance of the refurbished blender was confirmed by preparing a blend of FRF with diesel fuel and the same surfactant type used in the work from the 1980s. The blender was fitted with special sampling ports upstream and downstream of the Kenics static mixers so that blending performance could be carefully evaluated for varying flow rates of the emulsifier, fuel, and water. The maximum full flow capacity was 1.67 GPM (100 GPH). Ratios of fuel, water and emulsifier were variable and controllable. Samples were drawn into a graduated cylinder and the cylinder was allowed to sit for a specific period of time so that the settling characteristics FRF mixture could be observed. The goal was to determine the range of flows that produced a homogeneous and stable fluid at the blender output.

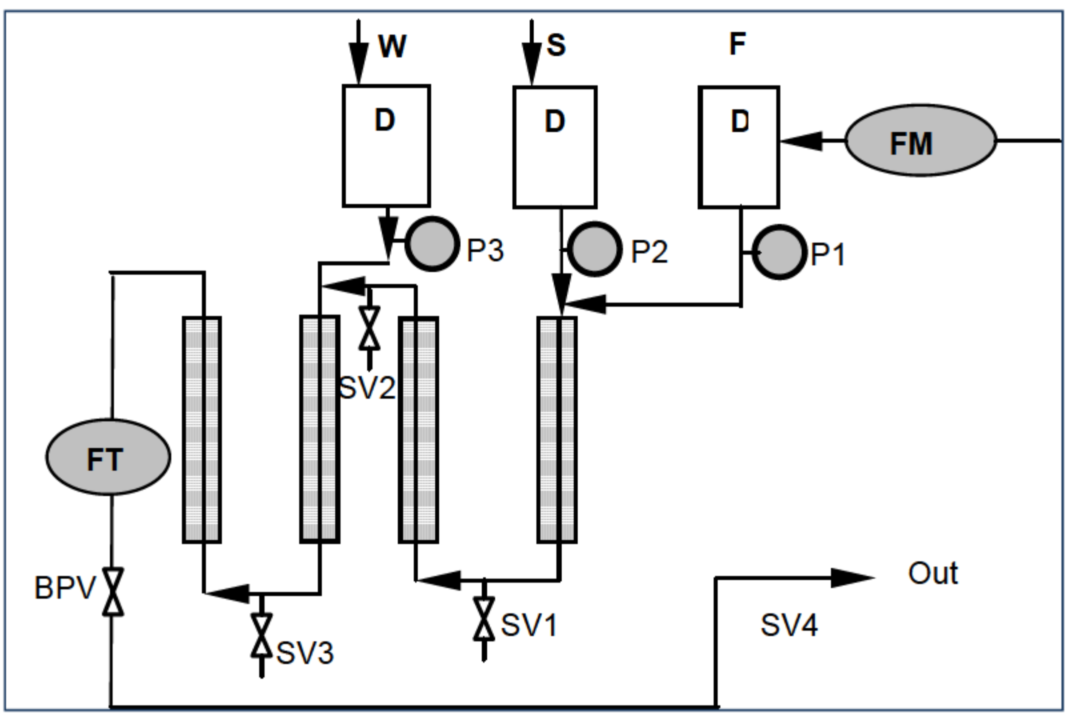



**Figure 26. Schematic Diagram of Slightly Modified Legacy Blender**

Samples taken at SV1 showed how well the surfactant and fuel mixed in the first static mixer. Samples taken at SV2 showed effectiveness of a second mixer in series with the first. Samples

taken at SV3 showed the effectiveness of static mixer number 3 for mixing in the water. Samples taken at SV4 (the output) showed the quality of the final product.

The legacy FRF blender served as a test bed for investigating a number of mixing issues; however, the work reported herein is focused on the performance of the static mixers. The flow condition for the first test was 1.4 GPM for a Haltermann diesel fuel, 0.021 GPM for the surfactant, and 0.16 GPM for the water for a total through put of approximately 1.581 GPM [88.5 % fuel, 1.3% surfactant, and 10.1% water on a volume basis]. Thus the unit was running at 1.58 GPM (94.8 GPH), which is near its maximum capacity of 1.67 GPM (100 GPH). Pressures at P1, P2, and P3 were 70 psi, 72 psi, and 50 psi respectively. Samples taken at sample valves SV1 and SV2 were clear and homogeneous indicating that the surfactant and fuel blended well. However the 100 ml samples taken at SV3 and SV4 were milky and pale yellow in color. These samples were allowed to settle. After 18 hours it was observed that separation of components within the sample jars was apparent. A white layer of fluid representing approximately 18% of the volume settled to the bottom of the sample jar. Observations after 42 hours showed essentially no change in the separation levels. Since the concentration of the surfactant was low (compared to a more reasonable 4 to 6%), it is not surprising that incomplete mixing occurred.

Testing showed that a stable FRF composed of 10% water, 6% surfactant, and 84% Haltermann fuel could be blended at a through put rate of 100 gallons per hour. The four-inline static mixers appeared to function well. Two of these mixers were needed to mix the water feed stream with the fuel/surfactant feed stream. At the maximum throughput, the mean velocity through the 24 inch long mixer was approximately 2.7 ft/sec (residence time ≈ ¾ second) and the fluid was rotated through approximately 22 elements that imparted significant rotation to the fluid. Surprisingly, the pressure drop was rather low at 10 psi per mixer. Based on the performance of these mixers, they would be an excellent choice for a field unit. Scaling up to ten times the flow rate or more would be well within the design parameters of the current products. The test data showed that these mixers are a mixing solution for diesel based FRF with at least one type of surfactant at a production rate of 100 gallons per hour. Also, based on the blending results obtained from the Legacy Blender (Figure 27), it was apparent that the static mixer(s) can blend JP-8, surfactant, and water.

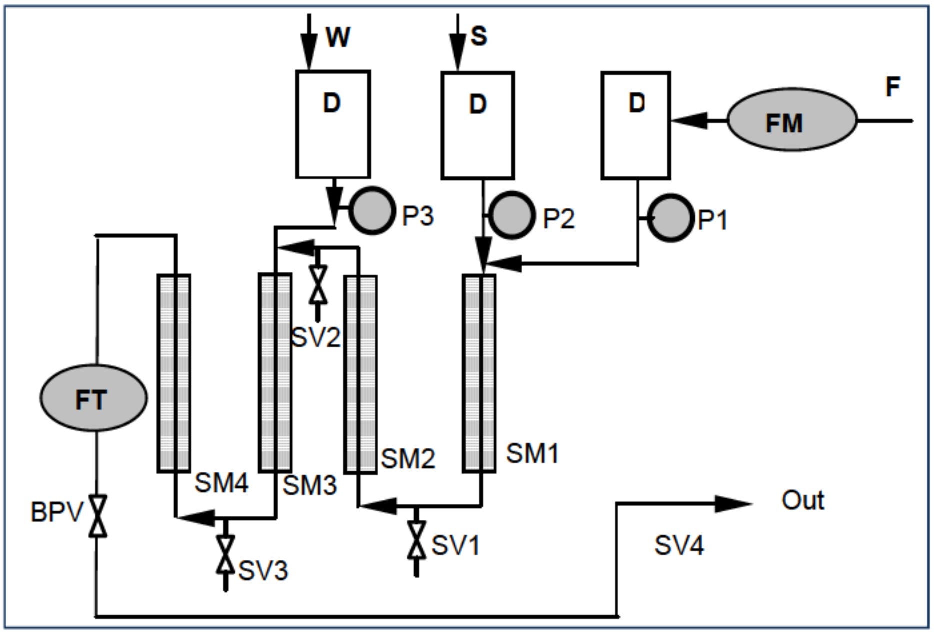



**Figure 27. Schematic Diagram of Modified Legacy Blender**

## 3.13 Equipment Compatibility

***Rotary Fuel Injection Pump Test***

The compatibility of JP-8 FRF with a rotary type fuel injection pump was determined by a 500 hour test. This pump type is used on all variants of the HMMWV. The test pump and 8 fuel injectors were mounted on a pump flow test rig. After 500 hours test time, all injectors were performing adequately. Overall, end of test pump condition and flow performance was equivalent to tests conducted using JP-8. In summary, no pumps parts failed during a standardized test with FRF. A test report is attached as Appendix A.

***Diesel Engine Performance Testing***

Because the FRF blends contain up to 10% water, there was a need to assess possible engine performance changes when operating on FRF blends. Two high usage density, compression ignition engines were chosen from current Army tactical vehicles to represent legacy and current diesel engine technology for FRF compatibility testing. The first engine was the Caterpillar

(CAT) C7, a 330hp 7.2L direct injected, turbocharged, intercooled, inline, six-cylinder, diesel engine; used in many vehicles including the Family of Medium Tactical Vehicles (FMTV), IAV Stryker, and many Mine Resistant Ambush Protected (MRAP) variants. The second engine was the General Engine Products (GEP) 6.5L(T), a 190-hp, pre-chamber injection, turbocharged, V8 diesel engine. It is used in the High Mobility Multipurpose Wheeled Vehicle (HMMWV). The results are given in a separate report and summarized below.[4]

It was found that FRF blends can be successfully used in typical compression ignition engines with an associated power loss depending on FRF blend composition. Typical engine output losses vary from 3 to 9% in peak power and torque depending on injection system configuration and FRF blend chemistry. During testing, no mechanical issues, due to water, emulsifier, and/or MCA in the fuels, were encountered with the use of FRF blends. In addition, it was found that FRF emulsion quality had no significant impact on engine function. However, poor quality emulsion had significantly reduced blend stability after exposure to diesel engine operating conditions. It is also expected that FRF use in most compression ignition engines would decrease the production of nitrogen-oxide emissions; but, due to various emission-measuring equipment problems, full engine-emissions characterizations were not obtained

**HMMWV Vehicle Testing**

A HMMWV equipped with a GEP 6.2L engine was refurbished. The fuel system had a complete overhaul in preparation for a more accurate monitoring of FRF compatibility. The HMMWV received a new fuel tank, fuel lines, lift pump, filter, injection pump, injectors, and the new cylindrical style fuel level sender.

The 6.2L HMMWV was operated at SwRI's Mileage Accumulation Dynamometer (MAD) facility. The goal of the program was to accumulate 15,000 miles on FRF. A 500 gallon tank was acquired for this testing so FRF could be blended in large batches, and the HMMWV could be continuously fueled. The FRF was blended from JP-8 consisting of 10% water and 6% Schercomid emulsifier, without MCA.

The HMMWV operated on a slightly modified test-cycle derived from the report ADA 449160[2]. The average speed for the test cycle was 30.5 MPH. Oil changes were scheduled for every 2,500 miles and transmission fluid changes every 7,500 miles. Samples were collected and analyzed. The 15,000 mile test successfully completed using FRF. A test report covering the MAD Testing was completed. See Appendix B for the complete test report. A summary of the results is given here:

- A 6.2L HMMWV accumulated 15,000 miles on FRF using a simulated driving cycle
- There were no fuel related hardware failures during operation
- The Stanadyne injection pump showed high levels of wear on some components, but still functioned adequately. The severe wear on the return fuel piston could be reason for concern.fuel injectors showed normal wear
- The fuel filter and water separator still functioned normally at the end of testing
- The fuel tank, lines, fittings, lift pump, and level sender functioned normally at the end of testing
- The used fluid analysis showed no abnormal wear

***Evaluation of JP-8 FRF in Caterpillar C7 Engine***

Engine compatibility of JP-8 FRF was determined by conducting a 210 hour Tactical Wheeled Vehicle endurance test using a Caterpillar C7 engine. The C7 engine is used in the Stryker Vehicle and the Army's Family of Medium Tactical Vehicles (FMTV'S). The test was conducted at 260°F oil sump temperatures (OST) to simulate engine operation in high ambient temperature locations. The engine completed the 210 hour test. The high OST caused substantial oil degradation by end of test. This was not fuel related. At end of test, engine power was reduced approximately 10% by reduced fuel flow due to lacquering in 2 fuel injectors. Additional research is recommended to determine the exact source of the injector deposits. See Appendix C for the complete test report.

***Evaluation of Fuel Filter compatibility***

Modified SAE J1488 Fuel/Water (emulsified) Separation Efficiency Tests were performed using FRF on two fuel filters/water separators utilized in engines powering high density wheeled vehicles in the Army inventory. The objective of this testing was to determine the impact of fire resistant fuel on fuel filters that are used in military equipment. The FRF blend was developed adding 6% surfactant and 10% water to JP-8. The filters tested were: Detroit Diesel Fuel Filter, Water –Separator, PN23516189 CL10-0603 and Caterpillar Element, Fuel Filter, Water-Separator, PN 326-1643 CL10-0604.

The testing results indicate that in both filters fuel/water separation efficiencies were impacted after exposure to FRF. The data indicated large volumes of water were retained by the filter during FRF exposure, resulting in poor fuel/water separation.  FRF fuel had no impact on filter capability to capture particulates.

***Literature Review Regarding PuriNOx***

To gain insight into equipment compatibility with emulsified fuels TFLRF staff reviewed "TXDOT Emulsified Diesel Fuel Final Report" by Ron Matthews[6]. As expected fuel consumption increased with the emulsified fuel. Because the fuel was a milky macro-emulsion, it interfered with an optical sensor on the 6.5L diesel engines. The results of this review are presented in Appendix D.

# 4.0 SUMMARY

This project documented the successful formulation and use of Fire Resistant Fuel including the following aspects:

- Additives for blending FRF from diesel fuel, JP-8, and water with up to 1000 ppm of solids.
- Mist control additive to reduce or eliminate the fireball aspect of fuel fires and thereby increase survivability.
- Ballistics testing, methods, and documented results.
- Design considerations for FRF blending equipment.
- Diesel engine performance.
- FRF blends made with higher flash point fuels (diesel fuel) performed consistently better in emulsion stability and flammability testing compared to blends made with lower flash point fuels such as JP-8.

A) *Formulation Studies*

1. Best Emulsifier & why

   The Schercomid ODA emulsifier system was found to be the best overall emulsifier to meet the goals of the project. This emulsifier was found to give acceptable emulsifier performance over the largest temperature span. It also gave acceptable performance in relation to water quality and emulsion stability in long term storage (approximately 2-4 weeks).

2. Effect of water quality (ETDA effect)

   Depending on the fuel (primarily aromatics content) some emulsions were unstable when made with water having more than 200-250 ppm of total dissolved solids. It was found that addition of EDTA to the blend during blending enabled the formation of stable emulsions with water containing up to about 1000 ppm of dissolved solids.

3. Stability

   Low-temperature stability of emulsions continues to be a concern. Some emulsions, depending on fuel and water quality, maintained stability to several degrees below 0°C. But most emulsions tended to break at about this temperature. We were able to recombine the components with minimal mixing but the emulsion did not have the same, typical, clear appearance as emulsions prior to freezing.

4. JP-8 vs DF-2 Emulsions

   Emulsions made with diesel fuel versus emulsions made with JP-8 were both easier to make (required less mixing) and were more stable. Diesel fuel emulsions tended to tolerate higher levels of dissolved solids in the water as well. This does not seem to be a matter of aromatics content only but that was a large factor. Fuel viscosity may also play a part in this difference.

5. Mist Control Additive Effects (Degradation in Engines)

   Engine testing demonstrated that mist control additive will degrade with successive passes through the engine fuel system. While the degraded polymer is still 1-3 orders of magnitude higher in average molecular weight that fuel molecules, its efficacy as a mist control additive is certainly reduced.

C) *FRF Blending System*

- Plans were prepared for FRF Blending Systems that maximizes use of existing Army petroleum and water handling equipment. Size options were 750, 1500, or 3000 gallon per hour of FRF.
- A legacy FRF blender was updated and used for blend studies that required up to 100 gallons per hour.

D) *Equipment Compatibility*

1. JP-8 FRF was compatible with a rotary fuel injection pump used on the HMMWV. This was determined by completing a 500 hour pump endurance test. (Appendix A)

2. The effect of various FRF blends on Army diesel engine performance was determined. For diesel FRF the power output was approximately equivalent to engine operation on JP-8. For JP-8 FRF, power was reduced by up to 9% compared to JP-8.

3. JP-8 FRF was found compatible with a HMMWV. The vehicle successfully completed 15,000 miles of testing on a mileage accumulation dynamometer using JP-8 FRF. There were no fuel hardware related failures during the test. (Appendix B)

4. JP-8 FRF was found to be compatible with the Caterpillar C7 engine. This was determined by successfully completing a 210 hour Tactical Wheeled Vehicle Endurance Test. (Appendix C)

## 5.0 RECOMMENDATIONS

1. It is recommended that FRF be approved for use in selected tactical applications to reduce the risk of fire and pool burning of fuel.

2. Diesel fuel blends are recommended, as opposed to JP-8 fuel blends, where possible. These blends tend to be easier to prepare and more stable (i.e., diesel blends exhibit more stable emulsions, compared to JP-8 blends, under similar storage/handling conditions; increased storage stability times vary with storage conditions)..

3. The typically higher flash point of diesel fuel, compared to JP-8, resulted in significant improvements in ballistic test results.

4. EDTA is a useful addition to the blend whenever the total dissolved solids content of the water exceeds about 200 ppm. The EDTA additive should become part of the standard additive package for blending.

5. Further development of improved Mist Control Additives that contain shear resistant properties is recommended.

# 6.0 REFERENCES


1. Wright, B.R. and Kanakia M.D. (1987) Final review of U.S. Army Fire Resistant Fuel Program. Interm Report BFLRF No. 244.

2. González, M.A., H. Rivas, X. Gutiérrez, and A. León, Performance and Emissions using Water in Diesel Fuel Microemulsion, 2001-01-3525. *Society of Automotive Engineers, Inc.*, 2001.

3. Interim Report TFLRF No. 377, *"HMMWV Field Operation Data Collection and Analysis",* received DTIC accession number ADA449160.

4. Interim Report TFLRF No. 403, "*Impact of Fire Resistant Fuel Blends on Formation of Obscuring FOG",* received DTIC accession number ADA527929.

5. Interim Report TFLRF No. 410, *"Correlation of Laboratory Flame Propagation Testing Result with Ballistic Testing Utilizing Several Threats with Varying Explosive."*

6. Interim Report TFLRF No. 412, *"Impact of Fire Resistant Fuel Blends on Compression Ignition Engine Performance.",* received DTIC accession number ADA555377.

7. "TXDOT Emulsified Diesel Fuel Final Report" by Ron Matthews.

# APPENDIX A

## ROTARY FUEL INJECTION PUMP FIRE RESISTANT FUEL (FRF) ENDURANCE TESTING

Project 08.14734.03

**Stanadyne Rotary Pump DB2-5149**

*Test Fuel Description: JP8-FRF (84% JP8, 6% Surfactant, 10% DI H2O)*

**Test Temperature: 40°C (104°F)**
**Test Number: 100126-JP8FRF**
**Start of Test Date: January 26, 2010**
**End of Test Date: March 4, 2010**
**Test Duration: 500 Hrs**

*Conducted for*

**U.S. Army TARDEC**
**Force Projection Technologies**
**Warren, Michigan**

## CYCLE DESCRIPTION

Stanadyne fuel injection pump endurance testing consists of the fuel injection pump operation on a controlled test stand for a specified duration. Testing continued until the specified duration was met, or until major performance degradation was experienced, whichever occurred first. The Stanadyne fuel injection pump used for testing was a rotary style pump used in a pump line nozzle configuration as found in the U.S. Military's High Mobility Multipurpose Wheeled Vehicle (HMMWV). All factory pumps, high pressure lines, and fuel injectors were used to ensure similar performance on the test stand as would be seen in vehicle. The test cycle was used to determine varying fuel properties impact on pump and injector performance over an accelerated life span. This was accomplished by operating the pumps at rated speed (fuel flow) conditions as outlined in Stanadyne calibration specifications, while supplying test fuel at controlled inlet pressure and temperature conditions. Overall pump performance degradation could be monitored throughout testing in several ways; large changes (increase/decrease) of injected flow rate, increases in fuel pump return fuel temperature, increases in pump body temperature, and changes in pump housing pressure. All important pump parameters are monitored and recorded throughout testing to monitor pump performance versus test time.

## OPERATING SUMMARY

Test cycle operating parameters can be seen below in Table A16.

**Table A16 – Test Cycle Operating Parameters**

| Parameter | Test Conditions |
|---|---|
| Pump Speed, RPM | 1700 +/- 10 |
| Fuel Inlet Pressure, psi | 3 +/- 1 |
| Fuel Inlet Temperature, °C | 40 +/- 5 |

Statistical information on pump operating conditions over the endurance cycle can be seen below in Table A17.

**Table A17 – Pump Operation Summary**

| Test Point | Description | Average | Std Dev |
|---|---|---|---|
| PUMP_SPD | Pump Speed [rpm] | 1700.70 | 2.95 |
| | | | |
| FLO_R | Injeted Flowrate [mL/min] | 743.54 | 7.73 |
| | | | |
| FUELIN_P | Fuel Inlet Pressure [psig] | 3.10 | 0.15 |
| TRNS_P_R | Transfer Pump Pressure [psig] | 78.69 | 1.12 |
| HSG_P_R | Pump Housing Pressure [psig] | 6.86 | 2.21 |
| | | | |
| RTRN_T_R | Fuel Return Temperature [°C] | 48.56 | 1.27 |
| FUEL_T | Fuel Tank Temperature [°C] | 27.76 | 3.49 |
| FUELIN_T | Fuel Inlet Temperature [°C] | 39.92 | 0.82 |

## PLOT

Graphical plots for key operating conditions can be seen below in Figure A28 through Figure A30.

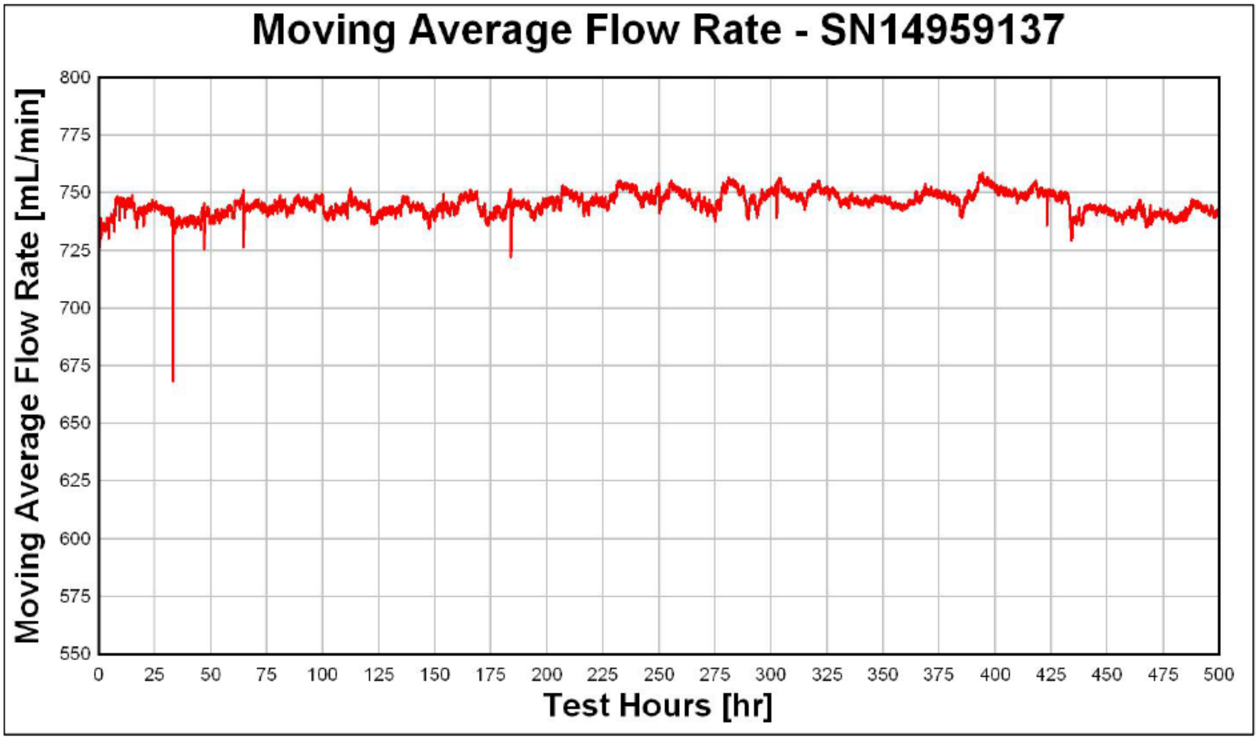



**Figure A28 - Pump Flow, Moving Average – SN14959137**

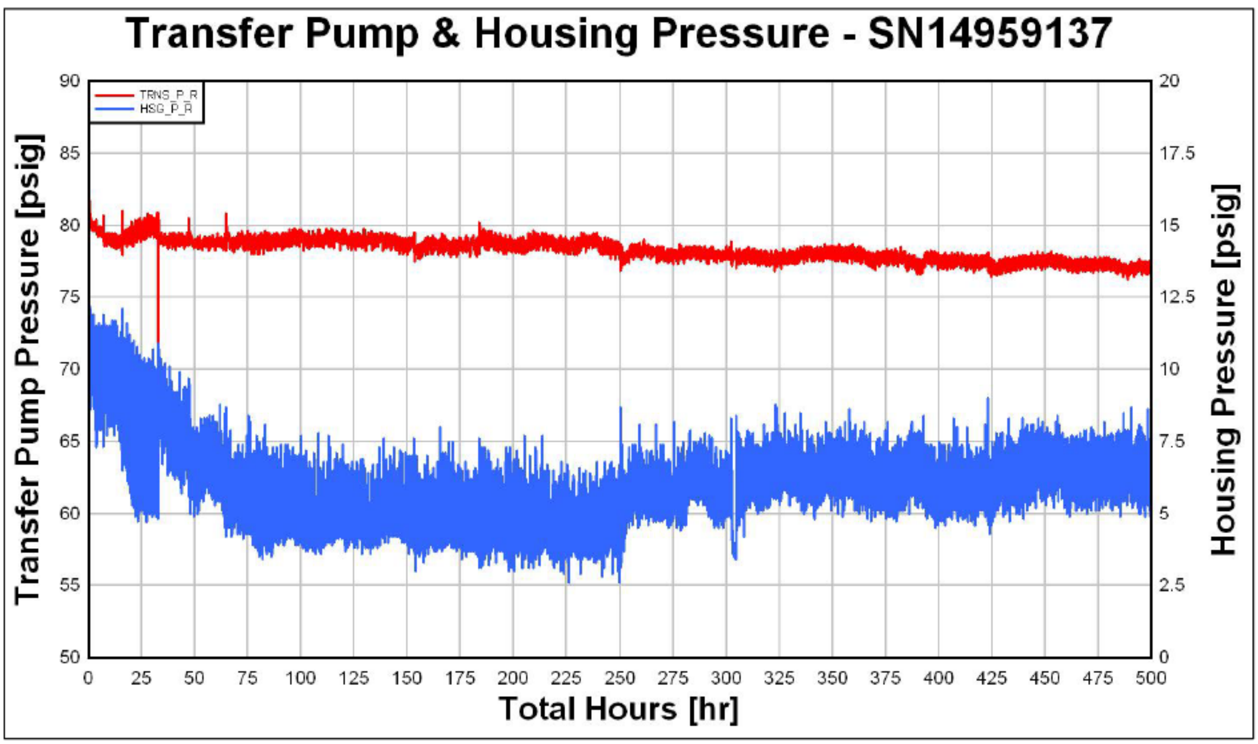



**Figure A29 - Transfer Pump & Housing Pressure - SN14959137**

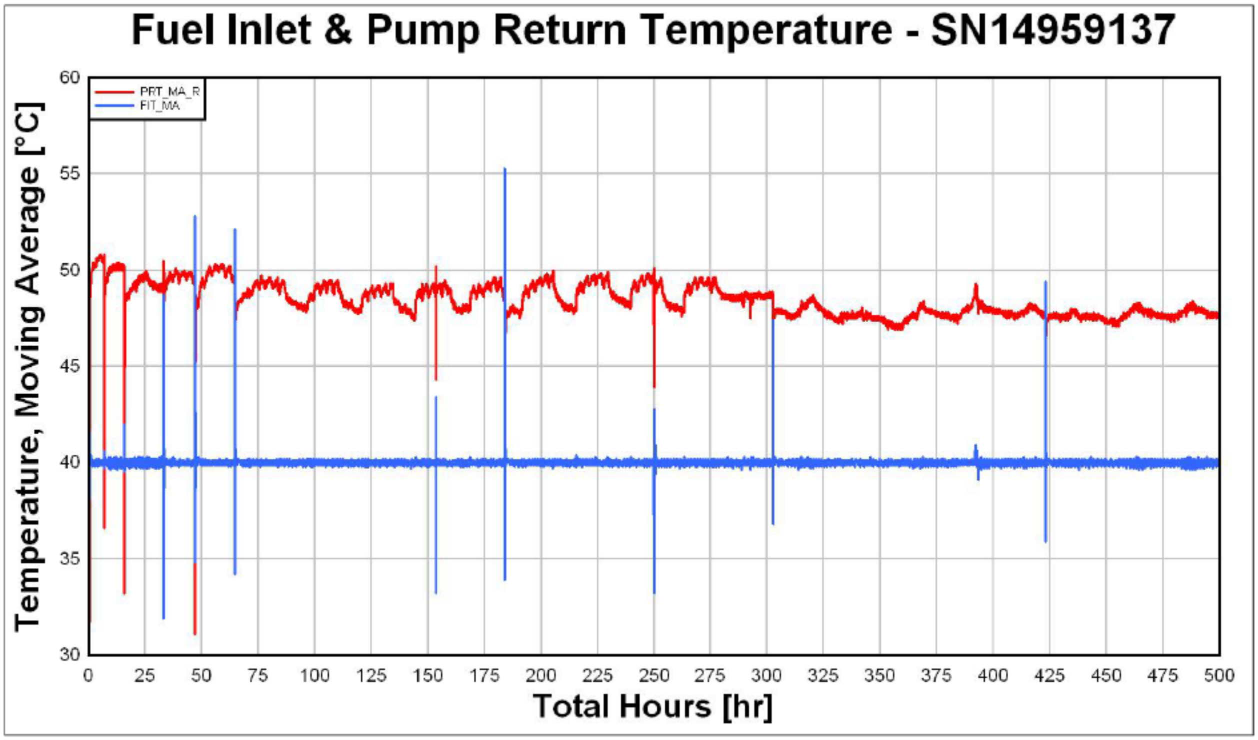



**Figure A30 - Fuel Inlet & Return Temperature, Moving Average - SN14959137**

## PUMP CALIBRATION

Before testing, injection pumps received a calibration to set key parameters to factory specifications as called out by Stanadyne. After testing, the pump was then recalibrated to determine the change in operating parameters for the test article. Results for pre and post test pump calibration can be seen below in Table A18. (*Note – Calibration data to be used as reference only)

**Table A18 - Stanadyne Pump Calibration, Pre and Post Test**

### Stanadyne Pump Calibration / Evaluation

| | |
|---|---|
| **Pump Type : DB2831- 5149 (arctic)** | **SN: 14959137** |
| **Test condition :** For FRF Equipment Compat bility Testing | |

| PUMP RPM | Description | Spec. | Before | After | Change |
|---|---|---|---|---|---|
| 1000 | Transfer pump psi. | 60-62 psi | 61 | 60 | 1 |
| | Return Fuel | 225-375 cc | 326 | 420 | -94 |
| | Fuel Delivery | 56 cc. Max. | 56 | 57 | -1 |
| 350 | Low Idle | 12-16 cc | 14.5 | 7.5 | 7 |
| | Housing psi. | 8-12 psi | 10 | 9 | 1 |
| | Cold Advance Solenoid | 0-1 psi. | 0 | 0 | 0 |
| 1700 | Fuel Delivery | 49 - 52 cc | 53 | 53 | 0 |
| | Advance | 3.5 - 4.5 deg. | 3.99 | 2.9 | 1.09 |
| 1750 | Fuel Delivery | 45 cc. min. | 53 | 53 | 0 |
| 1825 | Fuel Delivery | 31.5 cc min. | 37 | 51 | -14 |
| 1600 | Face Cam Fuel delivery | 21.5 - 23.5 cc | 22 | 22 | 0 |
| | Advance | 4 - 6 deg. | 4.48 | 4.7 | -0.22 |
| 750 | De-Energize E.S.O. | 4 cc max. | 0.5 | 0.5 | 0 |
| 1800 | Fuel Delivery | Record | 50 | 52 | -2 |
| | Transfer pump psi. | Record | 89 | 84 | 5 |
| | Housing psi. | Record | 9.5 | 8.5 | 1 |
| 1950 | High Idle | 15 cc max. | 2 | 13 | -11 |
| | Transfer pump psi. | 125 psi max. | 104 | 99 | 5 |
| 200 | Fuel Delivery | 43 cc min. | 52 | 53 | -1 |
| | Shut-Off | 4 cc max. | 0.5 | 0.5 | 0 |
| 75 | Fuel Delivery | 28 cc min. | 44 | 43 | 1 |
| | Transfer pump psi. | 16 psi min. | 23 | 20 | 3 |
| | Air Timing | -1 deg. (+/-.5) | -1 | -1 | 0 |
| | Date | | 12/3/2009 | 3/10/2010 | |

# METROLOGY

Before and after testing injection pumps were torn down and measured to document internal wear accumulated over the endurance cycle. The primary measurements taken were the transfer pump blade dimensions, and documentation of the roller to roller dimensions. This data can be seen below in Table A4.

A dimensional key for the transfer pump blade measurements can be seen in Figure A31.

**Table A19 - Transfer Pump Blade & Roller to Roller Dimensions**

**Blade & Roller-To-Roller Measurements**

| Pump Type : DB@2831-5149 | SN:14959136 | Test Number : JP8FRF |
|---|---|---|
| Fuel description : JP8 FRF | | |

| | Date: | 11/19/2009 | 4/5/2010 | |
|---|---|---|---|---|
| ***Dimensional Measurements*** | | ***0 hrs.*** | ***500 hrs.*** | ***Change*** |
| Transfer Pump Blade #1 | Dimension A | 13.802 | 13.791 | -0.011 |
| | Dimension B | 9.974 | 9.963 | -0.011 |
| | Dimension C | 12.673 | 12.673 | 0.000 |
| | Dimension D | 3.136 | 3.135 | -0.001 |
| | Dimension E | 3.137 | 3.136 | -0.001 |
| | Dimension F | 3.136 | 3.136 | 0.000 |
| Transfer Pump Blade #2 | Dimension A | 13.807 | 13.796 | -0.011 |
| | Dimension B | 10.007 | 9.993 | -0.014 |
| | Dimension C | 12.681 | 12.678 | -0.003 |
| | Dimension D | 3.136 | 3.135 | -0.001 |
| | Dimension E | 3.135 | 3.135 | 0.000 |
| | Dimension F | 3.136 | 3.134 | -0.002 |
| Transfer Pump Blade #3 | Dimension A | 13.803 | 13.797 | -0.006 |
| | Dimension B | 10.006 | 9.997 | -0.009 |
| | Dimension C | 12.681 | 12.681 | 0.000 |
| | Dimension D | 3.135 | 3.135 | 0.000 |
| | Dimension E | 3.135 | 3.135 | 0.000 |
| | Dimension F | 3.136 | 3.136 | 0.000 |
| Transfer Pump Blade #4 | Dimension A | 13.803 | 13 800 | -0.003 |
| | Dimension B | 9.968 | 9.956 | -0.012 |
| | Dimension C | 12.670 | 12.677 | 0.007 |
| | Dimension D | 3.136 | 3.136 | 0.000 |
| | Dimension E | 3.137 | 3.136 | -0.001 |
| | Dimension F | 3.137 | 3.137 | 0.000 |
| | Roller to Roller (in) | 1.9760 | 1.9675 | -0.008 |
| | Eccentricity (in.) | 0.0060 | 0.0100 | 0.004 |

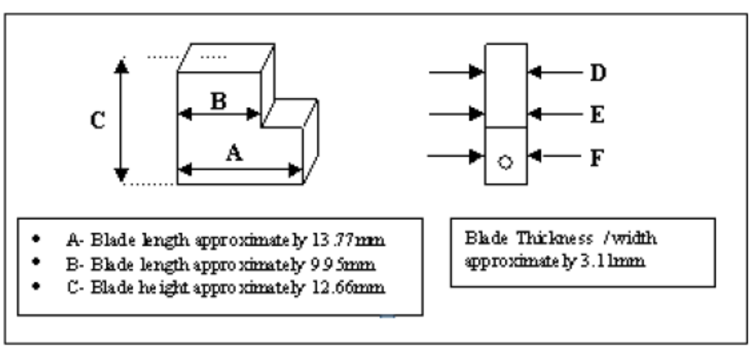



**Figure A31 - Dimensional Key for Transfer Pump Blade Measurements**

# RATINGS

After completion of testing, disassembled pump components received a visual rating to quantify the severity of component wear accumulated during testing. Ratings were evaluated on a scale of 0 to 5, with 0 representing a component in new condition, and 5 representing a failed component. Post test component rating information can be seen below in Table A20.

**Table A20 - Post Test Component Ratings**

## Stanadyne pump parts Evaluation

| | |
|---|---|
| **Pump Type : DB2831- 5149** | **SN: 14959137** |
| **Test condition : 500 Hour JP8-FRF Endurance** | **AL:** |

| Part Name | Condition of part | Rating |
|---|---|---|
| BLADES | Very light wear at rotor slots & liner contact | 1 |
| BLD. SPRINGS | Normal | 0 |
| LINER | Some polishing | 1 |
| TRANS.PUMP REG. | Mostly polishing wear with one scratch from rotor contact | 2 |
| REG. PISTON | Polishing wear in one spot | 1 |
| ROTOR | Normal - no wear | 0 |
| ROTOR RET. | Light wear from rotor contact | 1 |
| D-VALVE | Very lightly polished in small areas. (Broken spring : rating - 5 not known if fuel related) | 1 |
| PLUNGERS | Normal - no visible wear | 0 |
| SHOES | Light wear spots at plunger contact. Light scarring at roller contact. Light wear at leaf spring contact. | 2 |
| ROLLERS | Light scarring. Blue color. | 2 |
| LEAF SPRING | Light wear from shoe contact | 1 |
| CAM RING | Polished at roller contact points. | 1 |
| THRST. WASH. | Polished at weight contact | 1 |
| THRST. SLEEVE. | Light wear at gov. arm slots | 1 |
| GOV. WEIGHTS | Wear at foot from thrust washer contact. | 1 |
| LINK HOOK | Normal - no wear | 0 |
| M-VALVE | Normal - no wear | 0 |
| DR. SHAFT TANG | Lightly polished in small spots | 1 |
| DR. SHAFT SEALS | Normal | 1 |
| CAM PIN | Lightly polished | 1 |
| ADV. PISTON | Light scuffing wear. Strange grey color. | 3 |
| HOUSING | Normal. Grey color where head seats. | 1 |

# FUEL INJECTORS

## Stanadyne Rotary Pump Lubricity Evaluation

### 6.2L/6.5L Fuel Injector Test Inspection

| Test No. | Inj. Pump ID No. | Fuel | Inj. ID No. | Opening Pressure | Tip Leakage | Chatter | Spray pattern | Assy. Leakage | Pintle cond. | Lapped Surface | Date | Hrs. | Tech. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100126-JP8FRF | SN: 14959137 (Pre Test) | JP8 FRF | 9-10 | 1900 | dry | none | good | dry, no seepage | N/A | N/A | 1/21/2010 | 0 | REG |
| | | | 10-10 | 1925 | dry | none | good | dry, no seepage | N/A | N/A | 1/21/2010 | 0 | REG |
| | | | 11-10 | 1850 | dry | none | good | dry, no seepage | N/A | N/A | 1/21/2010 | 0 | REG |
| | | | 12-10 | 1900 | dry | none | good | dry, no seepage | N/A | N/A | 1/21/2010 | 0 | REG |
| | | | 13-10 | 1900 | dry | none | good | dry, no seepage | N/A | N/A | 1/21/2010 | 0 | REG |
| | | | 14-10 | 1900 | dry | none | good | dry, no seepage | N/A | N/A | 1/21/2010 | 0 | REG |
| | | | 15-10 | 1900 | dry | none | good | dry, no seepage | N/A | N/A | 1/21/2010 | 0 | REG |
| | | | 16-10 | 1925 | dry | none | good | dry, no seepage | N/A | N/A | 1/21/2010 | 0 | REG |
| | SN: 14959137 (Post Test) | JP8 FRF | 9-10 | 1700 | dry | none | good | dry, no seepage | N/A | N/A | 3/12/2010 | 500 | REG |
| | | | 10-10 | 1725 | dry | none | good | dry, no seepage | N/A | N/A | 3/12/2010 | 500 | REG |
| | | | 11-10 | 1675 | dry | none | good | dry, no seepage | N/A | N/A | 3/12/2010 | 500 | REG |
| | | | 12-10 | 1725 | dry | none | good | dry, no seepage | N/A | N/A | 3/12/2010 | 500 | REG |
| | | | 13-10 | 1725 | dry | none | good | dry, no seepage | N/A | N/A | 3/12/2010 | 500 | REG |
| | | | 14-10 | 1725 | dry | none | good | dry, no seepage | N/A | N/A | 3/12/2010 | 500 | REG |
| | | | 15-10 | 1725 | dry | none | good | dry, no seepage | N/A | N/A | 3/12/2010 | 500 | REG |
| | | | 16-10 | 1700 | dry | none | good | dry, no seepage | N/A | N/A | 3/12/2010 | 500 | REG |
| | | | Spec. : | 1500psig min | no drop off in 10 sec. @ 1400 psi | chatter | fine mist | dry, no seepage | shiny, no scratches | report | | | |

**Comments**

# PHOTOGRAPHS

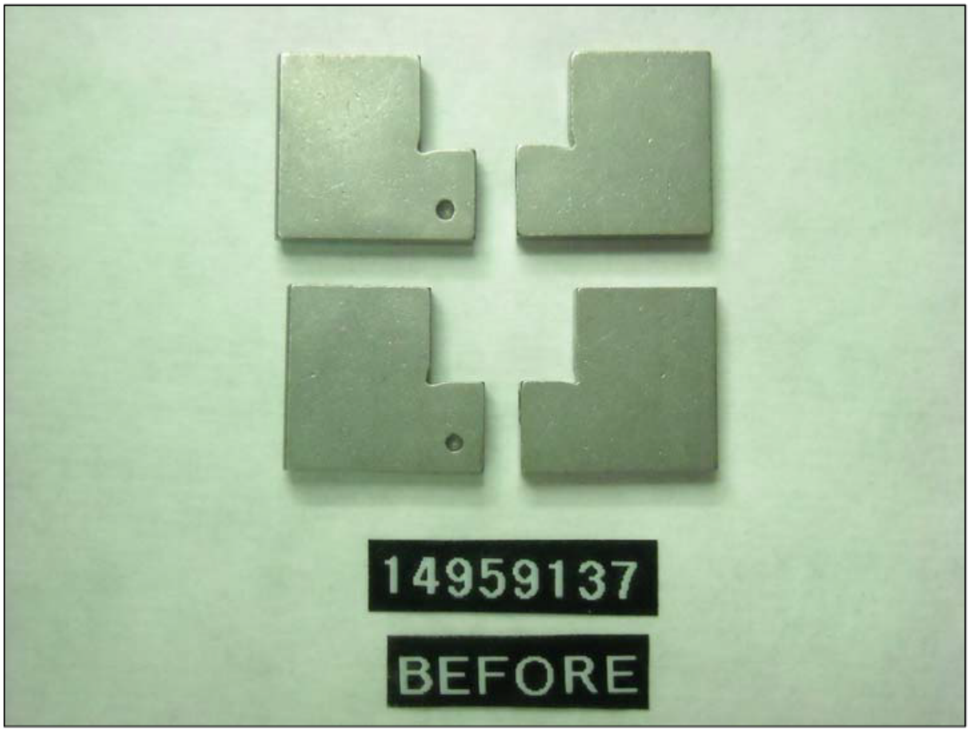



**Figure A32 - SN14959137 Transfer Pump Blades (Side), Before**

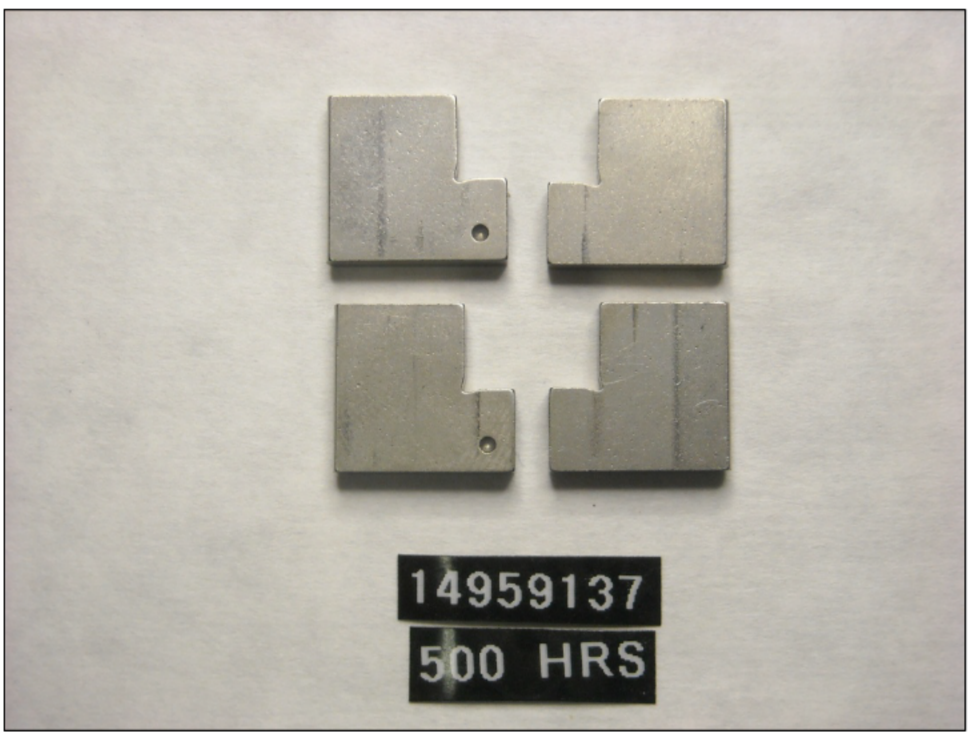



**Figure A33 - SN14959137 Transfer Pump Blades (Side), After**


**Figure A34 - SN14959137 Transfer Pump Blades (Profile), Before**

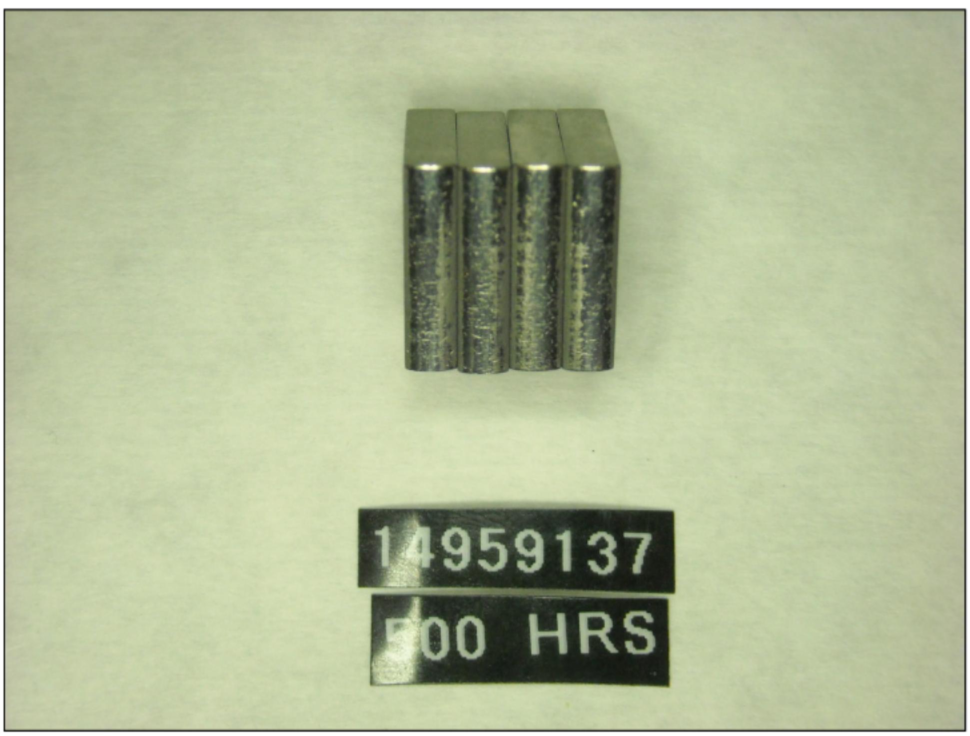



**Figure A35 - SN14959137 Transfer Pump Blades (Profile), After**

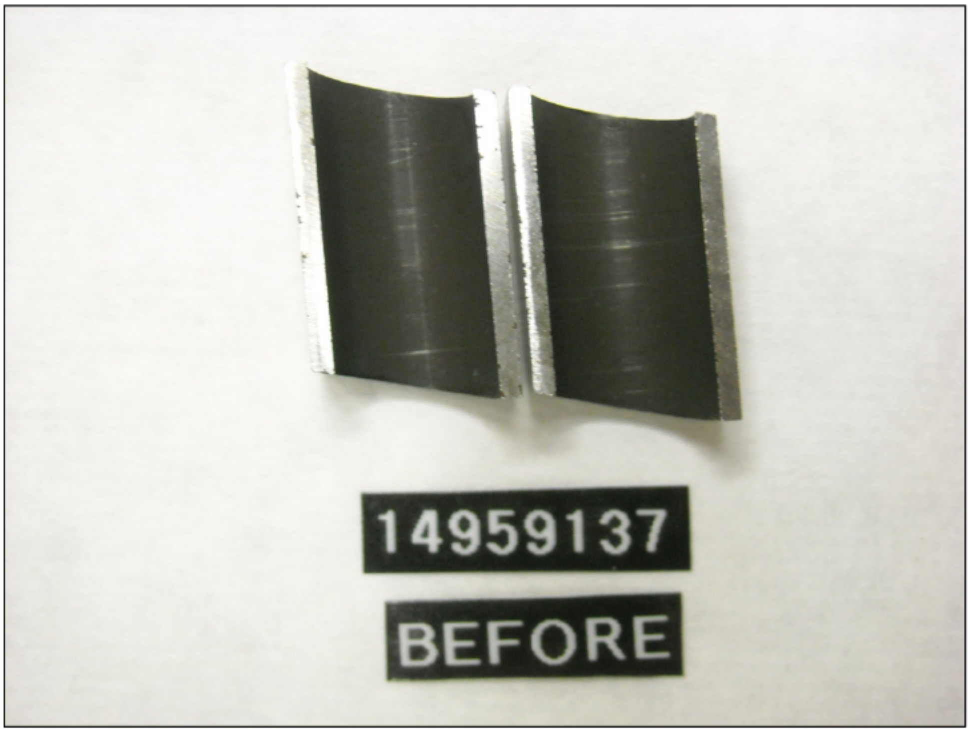



**Figure A36 - SN14959137 Shoes (Front), Before**

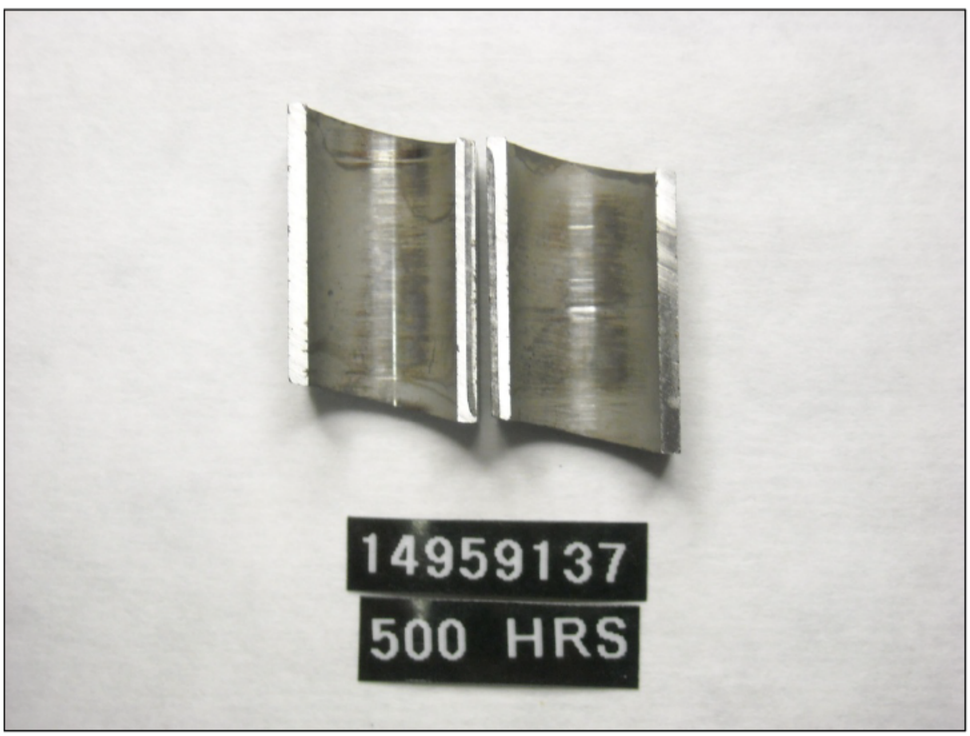



**Figure A37 - SN14959137 Shoes (Front), After**

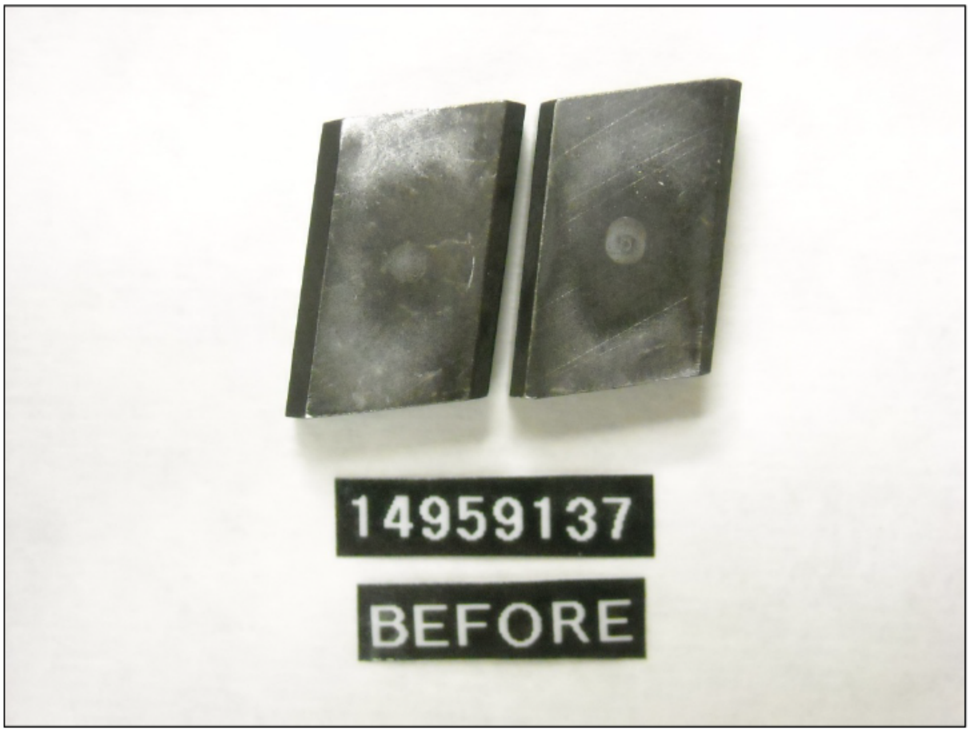



**Figure A38 - SN14959137 Shoes (Back), Before**


**Figure A39 - SN14959137 Shoes (Rear), After**


**Figure A40 - SN14959137 Rollers, Before**


**Figure A41 - SN14959137 Rollers, After**


**Figure A42 - SN14959137 Plungers, Before**


**Figure A43 - SN14959137 Plungers, After**

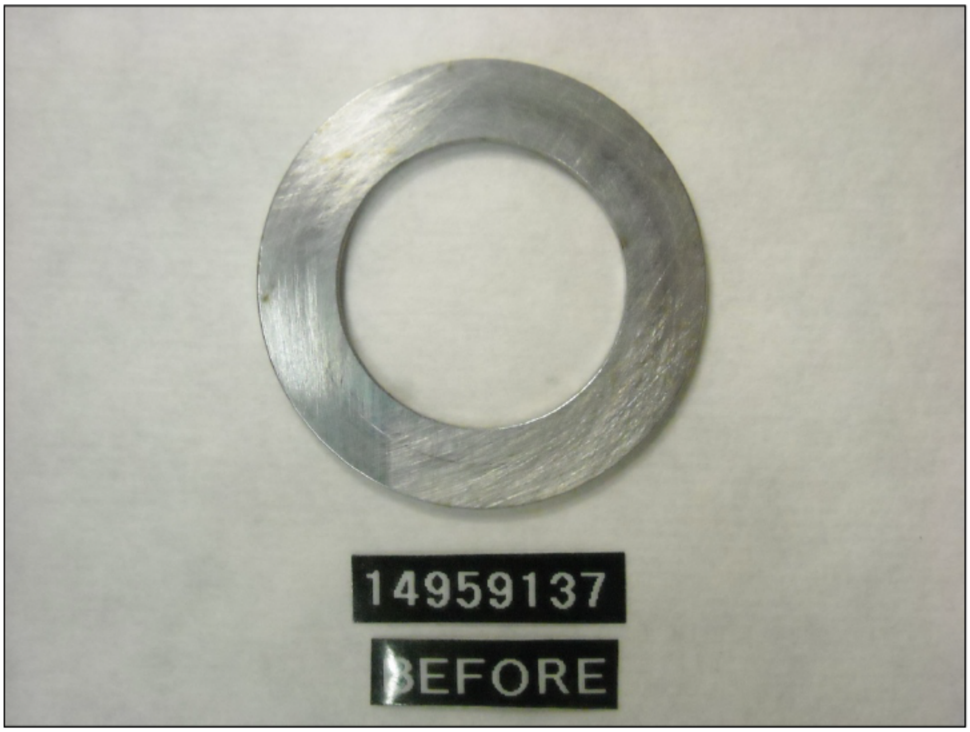



**Figure A44 - SN14959137 Thrust Washer, Before**


**Figure A45 - SN14959137 Thrust Washer, After**

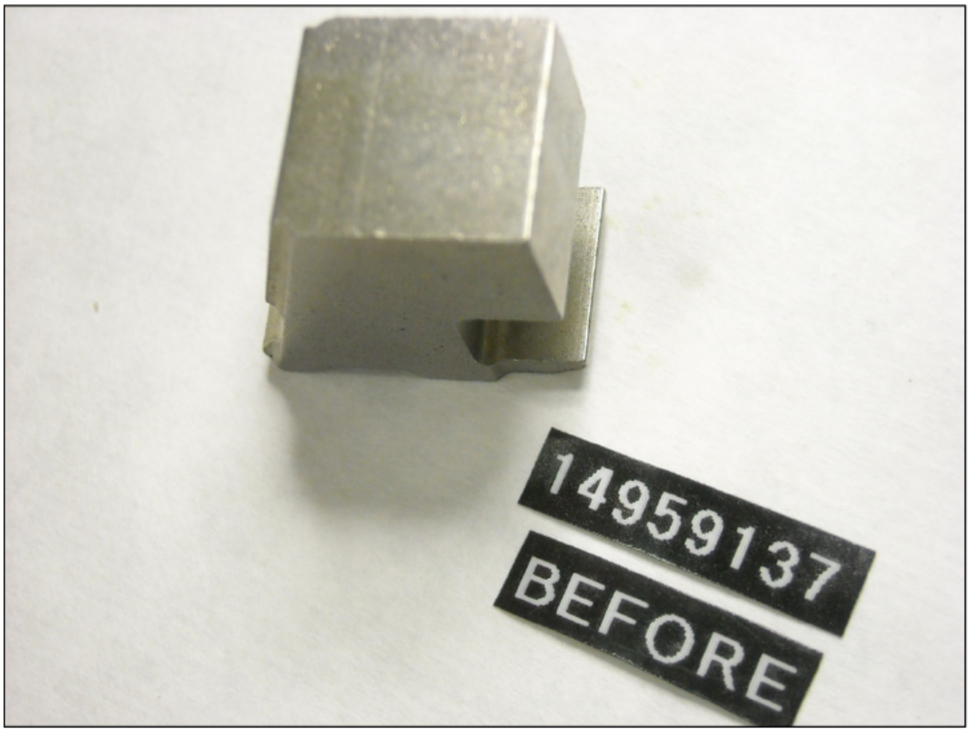



**Figure A46 - SN14959137 Governor Weight, Before**


**Figure A47 - SN14959137 Governor Weight, After**


**Figure A48 - SN14959137 Cam Ring, Before**


**Figure A49 - SN14959137 Cam Ring, After**


**Figure A50 - SN14959137 Transfer Pump Liner, Before**

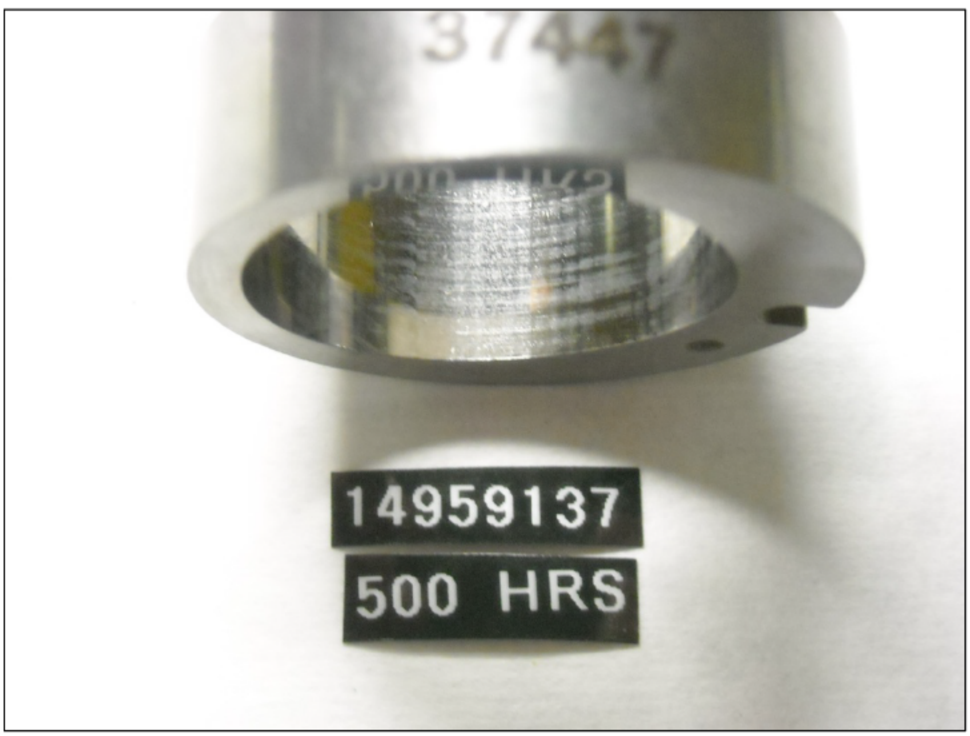



**Figure A51 - SN14959137 Transfer Pump Liner, After**

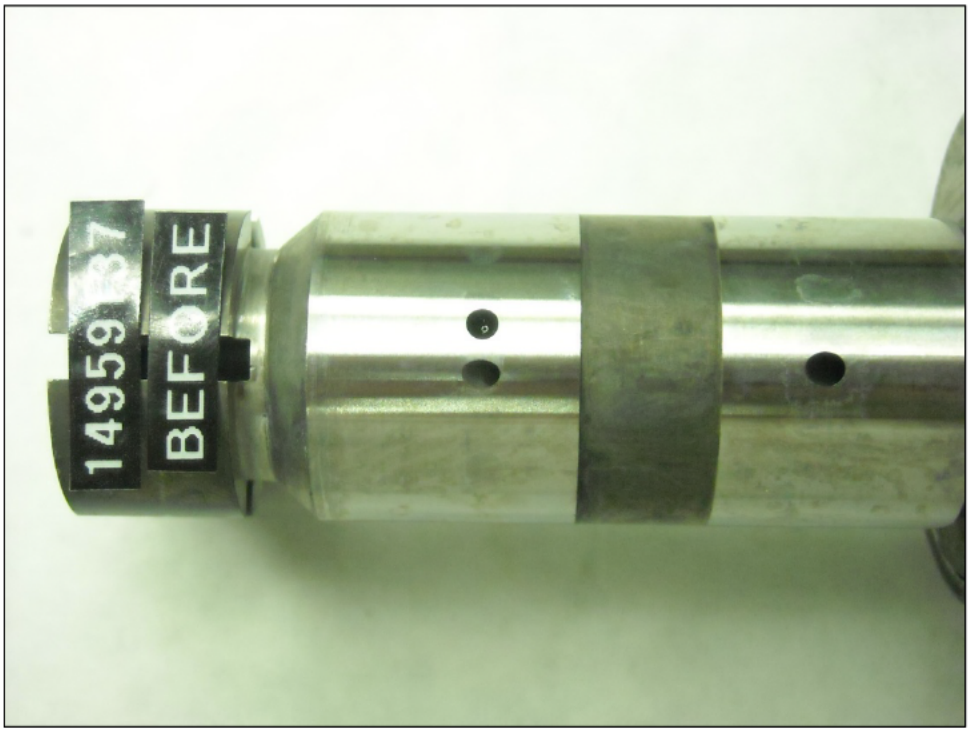



Figure A52 - SN14959137 Rotor (Front), Before


Figure A53 - SN14959137 Rotor (Front), After

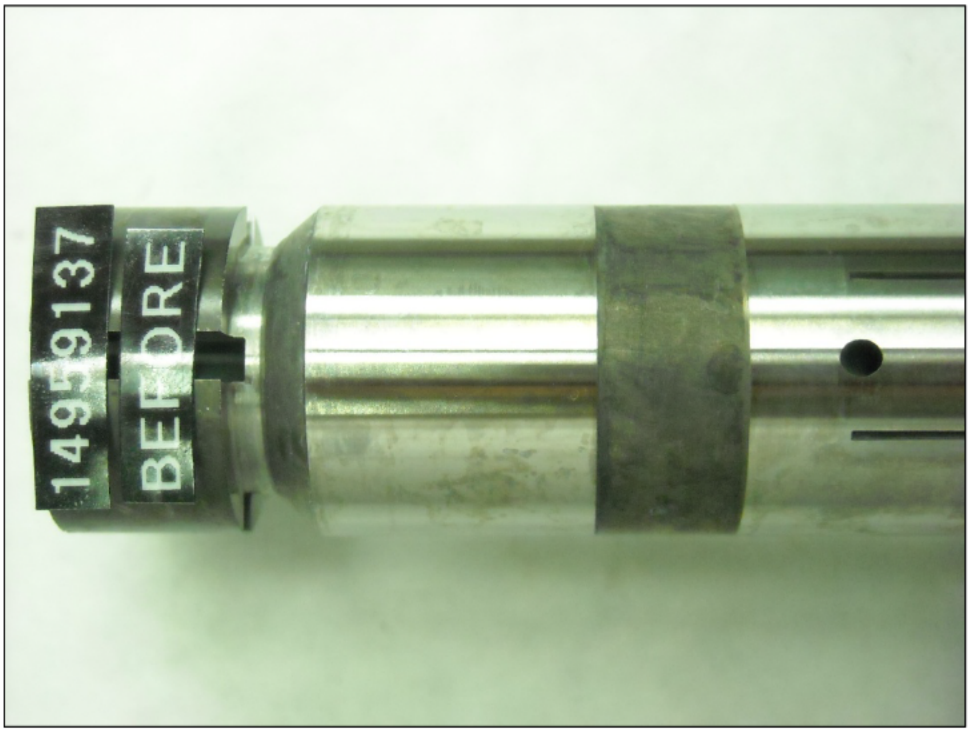



Figure A54 - SN14959137 Rotor (Back), Before


Figure A55 - SN14959137 Rotor (Back), After

APPENDIX B

HMMWV ON SITE DEMONSTRATION
FIRE RESISTANT FUEL (FRF) ENDURANCE TESTING

**Project 08.14734.03**

**6.2L HMMWV**

*Test Fuel Description: JP8-FRF (84% JP8, 6% Surfactant, 10% DI $H_2O$)*

**Start of Test Date: March 13, 2010**
**End of Test Date: June 21, 2010**
**Test Duration: 15,000 Miles**

*Conducted for*

**U.S. Army TARDEC**
**Force Projection Technologies**
**Warren, Michigan**

# INTRODUCTION

This test was designed to accumulate 15,000 miles of driving on a HMMWV while using JP-8 FRF. The entire fuel system on the HMMWV was replaced with new components prior to testing so it could be determined if there was any long term negative impact, on the hardware, from operating the vehicle on JP-8 FRF.

***Equipment***

Test vehicle: GFE HMMWV
S/N: 008854
Year: 1986
Engine: GEP 6.2L V8 Diesel, naturally aspirated

Fuel Injection Pump type: DB2831- 5209
S/N: 14247152

**Figure B1 - HMMWV at the Mileage Accumulation Dynamometer Facility**

# OPERATING SUMMARY

The HMMWV was operated on a single axel chassis dynamometer for the duration of the test. The vehicle's speed and load profile was primarily based on "HMMWV Field Operation Data Collection and Analysis", Interim Report TFLRF No. 377 or ADA 449160, and can be seen in Table B1.

Exhaust gas temperatures were used to correlate the road load as seen by the vehicle to the load applied by the dynamometer. Due to the smaller displacement engine and lower energy content of the fuel as compared with the vehicle in ADA 449160, the steady state road load values were matched to modes 5 and 10 and the full throttle values were matched to modes 2 and 7.

**Table B1 - ISO 8178 Field Weighting, from ADA 449160**

| ISO 8178 Field Weighting | | |
|---|---|---|
| Mode | Speed/% torque | Recommended Field Weighting |
| 1 | rated/100 | 0 |
| 2 | rated/75 | 0.01 |
| 3 | rated/50 | 0.08 |
| 4 | rated/25 | 0.15 |
| 5 | rated/10 | 0.07 |
| 6 | intermediate/100 | 0 |
| 7 | intermediate/75 | 0.04 |
| 8 | intermediate/50 | 0.19 |
| 9 | intermediate/25 | 0.13 |
| 10 | intermediate/10 | 0.06 |
| 11 | low idle | 0.27 |

In determining the simulated driving cycle, as shown in Table B2, modes 1 and 5 were discarded. Mode 11 was severely shortened from 0.27 to 0.0875 in order to shorten the time duration of the test. The remaining modes were proportionally increased to make up for the reduction in mode 11.

**Table B2 - Simulated Driving Cycle Parameters**

| Simulated Driving Cycle Parameters | | | | |
|---|---|---|---|---|
| Point # | Speed (mph) | % Grade | Time (s) | Distance (mi) |
| 1 | 25 | 0.0% | 450 | 3.1 |
| 2 | 25 | 5.7% | 300 | 2.1 |
| 3 | 45 | 0.0% | 525 | 6.6 |
| 4 | 45 | 5.7% | 75 | 0.9 |
| 5 | 25 | 0.7% | 975 | 6.8 |
| 6 | 45 | 1.2% | 600 | 7.5 |
| 7 | 25 | 3.4% | 356.25 | 2.5 |
| 8 | 45 | 0.7% | 281.25 | 3.5 |
| 9 | 25 | 3.4% | 356.25 | 2.5 |
| 10 | 45 | 0.7% | 281.25 | 3.5 |
| 11 | 25 | 3.4% | 712.5 | 4.9 |
| 12 | 45 | 0.7% | 562.5 | 7.0 |
| 13 | 0 | N/A | 525 | 0.0 |
| Total Distance Per Cycle | | | | 50.9 |
| Average Speed Per Cycle | | | | 30.6 |

Due to the high total time spent at modes 4 and 8 in Table B1, those modes were broken into 3 segments and alternated between as points 7 through 12 in Table B2. The alternating high load / low load method was done to prevent the dynamometer from overheating.

The cycle in Table B2 was performed for 15,000 miles or approximately 450 hours.

The HMMWV consumed approximately 1300 gallons of fuel for an average of 11.5 mpg or 19.8 lb/hr.

## FIRE RESISTANT FUEL

The fuel used was a homogeneous micro emulsion of 84% JP-8 (blended from Jet A), 6% Schercomid, and 10% de-ionized water. The fuel was blended in several batches (as needed) of roughly 300 to 400 gallons. Initially the FRF's water content was verified by running ASTM D6304 (Water Coulometric – Karl Fisher). Part way through the testing, the FRF blending unit was upgraded with mass flow sensors and the output stream density was adjusted on-the-fly to match the target mixture percentages.

## PLOTS

Representative plots for the HMMWV simulated driving cycle operating conditions can be seen below in Figures B2 and B3.

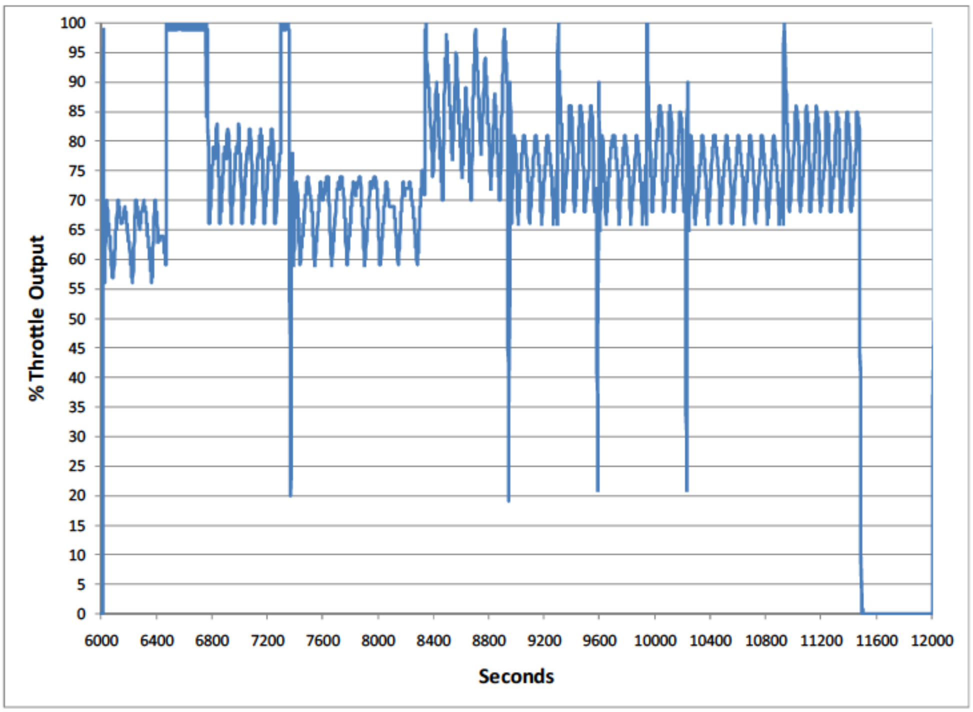



**Figure B2 - Simulated Driving Cycle Throttle Output**

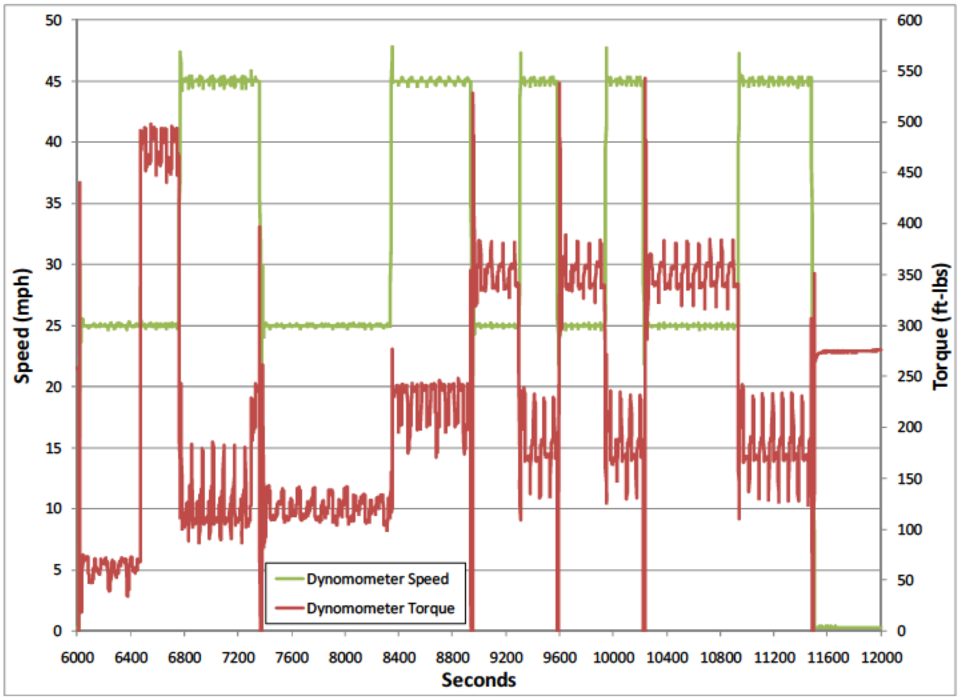



**Figure B3 - Simulated Driving Cycle Dynamometer Speed and Torque**

## PUMP CALIBRATION

Before testing injection pumps receive a calibration to set key parameters to factory specifications as called out by Stanadyne. After testing, the pump is then recalibrated to determine the change in operating parameters for the test article. Results for pre and post test pump calibration can be seen below in Table B3. (*Note – Calibration data to be used as reference only).

**Table B3 - Stanadyne Injection Pump Calibration**

# Stanadyne Pump Calibration / Evaluation

| | |
|---|---|
| **Pump Type : DB2831- 5209** | **SN: 14247152** |
| **Test condition :** WD03 HMMWV FRF Evaluation (15,000 Miles) | |

| PUMP RPM | Description | Spec. | Before | After | Change |
|---|---|---|---|---|---|
| 1000 | Transfer pump psi. | 60-62 psi | 60 | **56** | **-4** |
| | Return Fuel | 225-375 cc | 370 | **720** | **350** |
| | Fuel Delivery | 51.5 cc. Max. | 50 | 50 | 0 |
| 350 | Low Idle | 12-16 cc | 14 | **3** | **-11** |
| | Housing psi. | 8-12 psi | 10.5 | 10 | -0.5 |
| | Cold Advance Solenoid | 0-1 psi | 0 | 1 | 1 |
| 1750 | Fuel Delivery | 44.5 - 47.5 cc | 46 | 46 | 0 |
| | Advance | 3.75 - 4.75 deg. | 4.3 | **3.5** | **-0.8** |
| 1900 | Fuel Delivery | 31.5 cc min. | 38 | 39 | 1 |
| 1600 | Face Cam Fuel delivery | 21.5 - 23.5 cc | 22 | 22 | 0 |
| | Advance | 4 - 6 deg. | 4.45 | 4.17 | -0.28 |
| 1800 | Fuel Delivery | 44 cc min. | 48 | 47 | -1 |
| | Transfer pump psi. | Record | 87 | 83 | -4 |
| | Housing psi. | Record | 9.5 | 8 | -1.5 |
| 2025 | High Idle | 15 cc max. | 10 | **24** | **14** |
| | Transfer pump psi. | 125 psi max. | 100 | 90 | -10 |
| 200 | Fuel Delivery | 40 cc min. | 44 | 43 | -1 |
| | Shut-Off | 4 cc max. | 0 | 0 | 0 |
| 75 | Fuel Delivery | 26 cc min. | 34 | 31 | -3 |
| | Transfer pump psi. | 16 psi min. | 20 | 20 | 0 |
| | Air Timing | -1 deg. (+/-.5) | -1 | -1 | 0 |
| | Fluid Temp. Deg. C | | | | |
| | Date | | 8/21/2009 | 8/5/2010 | |

There was severe wear on the return fuel piston. Although not uncommon when compared to other FRF testing that has been done on these pumps, the severity of the wear is much worse. This is most likely due to the pump constantly changing load levels throughout the test. Stanadyne pump tests that are performed on a stand are operated only at one load point for the entire test.

## FUEL INJECTORS

As seen in Table B4, all of the fuel injectors finished the test in fully functional condition.

## Table B4 - Fuel Injector Calibration

| Inj. Pump ID No. | Fuel | Inj. ID No. | Opening Pressure (pre/post) | Tip Leakage (pre/post) | Chatter (pre/post) | Spray pattern (pre/post) | Assy. Leakage | Pintle cond. | Date (pre/post) | Hrs. | Tech. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SN: 14247152 | JP8-FRF (84% JP8, 6% Surfactant, 10% DI H2O) | 1 | 2100 | none | good | good | none | good | 7/15/2010 | 450 | RG |
| | | 2 | 2050 | none | good | good | none | good | 7/15/2010 | 450 | RG |
| | | 3 | 2050 | none | good | good | none | good | 7/15/2010 | 450 | RG |
| | | 4 | 2025 | none | good | good | none | good | 7/15/2010 | 450 | RG |
| | | 5 | 2050 | none | good | good | none | good | 7/15/2010 | 450 | RG |
| | | 6 | 2100 | none | fair | fair | none | sticky | 7/15/2010 | 450 | RG |
| | | 7 | 2000 | none | fair | fair | none | sticky | 7/15/2010 | 450 | RG |
| | | 8 | 2100 | none | good | good | none | good | 7/15/2010 | 450 | RG |
| | | Spec. : | 1500psig min | no drop off in 10 sec. @ 1400 psi | chatter | fine mist | dry, no seepage | shiny, no scratches | | | |

**Comments :** ***The pintle on injectors 6 & 7 feels sticky. The chatter is not as strong as the rest. They are still functional. Visually there is no obvious wear due to the fuel. All injectors exhibited similar wear due to extended heat cycling. All injectors also had some carbon deposition around the wave washer near the tip.***

# OIL AND TRANSMISSION FLUID ANALYSIS

The oil used for this test was MIL-PRF-2104G. The oil was changed every 2500 miles. The transmission fluid used was Dexron III (this HMMWV was equipped with a GM 3L-90 transmission). The transmission fluid was changed every 7500 miles. All values for D5185 that were less than 1 ppm were not included in the following charts. Both the oil and transmission fluid analysis did not show unusual wear as seen in Tables B5 and B6.

## Table B5 - Oil Analysis

| Date Sampled | New Oil | 04/26/10 | 05/03/10 | 05/11/10 | 05/24/10 | 06/11/10 | 06/29/10 |
|---|---|---|---|---|---|---|---|
| Test Miles | n/a | 2500 | 5000 | 7500 | 10000 | 12500 | 15000 |
| ASTM D445 Viscosity @ 100°C (cSt) | 14.62 | 14.72 | 14.93 | 14.90 | 14.65 | 14.83 | 14.95 |
| ASTM D445 Viscosity @ 40°C (cSt) | 110.03 | 104.44 | 108.67 | 110.38 | 107.59 | 109.39 | 110.59 |
| ASTM D4739 Total Base Number - Buffer Point (mg KOH/g) | 8.31 | 7.76 | 8.34 | 8.57 | 8.53 | 8.38 | 8.45 |
| ASTM D5185 Elemental Analysis (ppm) | | | | | | | |
| Aluminum (Al) | <1 | 5 | 2 | 2 | 2 | 2 | 3 |
| Boron (B) | 5 | 48 | 10 | 6 | 3 | 2 | 3 |
| Calcium (Ca) | 2595 | 2043 | 2993 | 3193 | 3174 | 3258 | 3280 |
| Chromium (Cr) | <1 | 12 | 4 | 3 | 2 | 4 | 6 |
| Copper (Cu) | <1 | 27 | 24 | 34 | 26 | 50 | 78 |
| Iron (Fe) | 2 | 72 | 42 | 46 | 38 | 70 | 113 |
| Lead (Pb) | <1 | 18 | 11 | 12 | 10 | 13 | 11 |
| Magnesium (Mg) | 12 | 581 | 124 | 34 | 15 | 12 | 11 |
| Molybdenum (Mo) | 2 | 11 | 4 | 5 | 3 | 5 | 7 |
| Nickel (Ni) | <1 | 4 | 2 | 2 | 1 | 2 | 3 |
| Phosphorus (P) | 1054 | 1100 | 1122 | 1100 | 1112 | 1097 | 1107 |
| Silicon (Si) | 4 | 25 | 10 | 9 | 8 | 10 | 17 |
| Sodium (Na) | 6 | 10 | 5 | <5 | <5 | <5 | 5 |
| Tin (Sn) | <1 | 10 | 4 | 4 | 3 | 5 | 6 |
| Zinc (Zn) | 1191 | 1385 | 1350 | 1331 | 1339 | 1353 | 1387 |
| Potassium (K) | 6 | 9 | 6 | <5 | <5 | <5 | <5 |
| ASTM D664 Total Acid Number - Buffer Point (mg KOH/g) | 2.2 | 2.41 | 2.24 | 2.32 | 2.41 | 2.43 | 2.45 |
| TGA Soot (wt.%) | 0.125 | 0.366 | 0.253 | 0.295 | 0.275 | 0.315 | 0.276 |

## Table B21 - Transmission Fluid Analysis

| Date Sampled | New Fluid | 05/11/10 | 06/29/10 |
|---|---|---|---|
| Test Miles | n/a | 7500 | 15000 |
| ASTM D445 Viscosity @ 100°C (cSt) | 5.99 | 5.97 | 6.12 |
| ASTM D445 Viscosity @ 40°C (cSt) | 29.91 | 30.29 | 28.28 |
| ASTM D4739 Total Base Number - Buffer Point (mg KOH/g) | 1.59 | 0.97 | 0.88 |
| ASTM D5185 Elemental Analysis (ppm) | | | |
| Boron (B) | 89 | 79 | 118 |
| Calcium (Ca) | 61 | 118 | 49 |
| Copper (Cu) | <1 | 128 | 38 |
| Iron (Fe) | <1 | 9 | 6 |
| Lead (Pb) | <1 | 5 | 12 |
| Magnesium (Mg) | <1 | 18 | 5 |
| Phosphorus (P) | 188 | 278 | 272 |
| Silicon (Si) | 5 | 16 | 10 |
| Zinc (Zn) | <1 | 72 | 23 |
| ASTM D664 Total Acid Number - Buffer Point (mg KOH/g) | 0.63 | 0.44 | 0.85 |

## SUMMARY

- A 6.2L HMMWV accumulated 15,000 miles on FRF using a simulated driving cycle
- There were no fuel related hardware failures during operation
- The Stanadyne injection pump showed high levels of wear on some components, but still functioned adequately. The severe wear on the return fuel piston could be reason for concern.
- The fuel injectors showed normal wear
- The fuel filter and water separator still functioned normally at the end of testing
- The fuel tank, lines, fittings, lift pump, and level sender functioned normally at the end of testing
- The used fluid analysis showed no abnormal wear

APPENDIX C

# EVALUATION OF JP-8 FIRE RESISTANT FUEL IN THE CATERPILLAR C7

## Project 08.14734.03

## Caterpillar C7

*Test Lubricant: LO-246362 – MIL-PRF-2104G OE/HDO Engine Oil*

*Test Fuel Description: JP8-FRF*

**Test Number: JP8FRF-C71-W-210**
**Start of Test Date: January 26, 2010**
**End of Test Date: February 19, 2010**
**Test Duration: 210 Hours**
**Test Procedure: Tactical Wheeled Vehicle**

*Conducted for*

**U.S. Army TARDEC**
**Force Projection Technologies**
**Warren, Michigan**

## INTRODUCTION

This test was used to evaluate JP-8 Fire Resistant Fuel (FRF) for use in military tactical vehicles using the Caterpillar (CAT) C7 engine and using the procedures outlined in the Tactical Wheeled Vehicle Cycle (CRC[2] Report No.406, Development of Military Fuel/Lubricant/Engine Compatibility Test). This work was completed in support of Work Directive 03, Feasibility of Fire Resistant Fuel for Ground Applications using JP-8.

## TEST ENGINE

The experimental fuel was evaluated in the Caterpillar (CAT) C7 turbocharged diesel engine, representative of engines currently fielded in the Family of Medium Tactical Vehicles (FMTV), the IAV Stryker, and some Mine Resistant Ambush Protected (MRAP) variants. Prior to testing, the engine was disassembled and measured for pre-test wear. Engine clearances and specifications were verified, and the engine was reassembled following standard assembly procedures.

## TEST STAND CONFIGURATION

The engine was mounted in a test stand specifically configured for CAT engine testing. Engine monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. An appropriately sized absorbing dynamometer was used to supply engine loading. Engine fuel and coolant temperatures were controlled with the use of liquid-to-liquid heat exchangers. Engine intake air was supplied at ambient conditions with engine exhaust vented to the atmosphere using the building blower system.

## ENGINE RUN-IN

Prior to testing, the engine was run-in using the following procedures outlined below in Table C1. The cyclic modes were repeated for a total of 6 cycles, for a total engine run-in runtime of approximately 6 hours.

[2] Available from Coordinating Research Council, www.crcao.org

**Table C1 - Test Engine Run-In Procedure**

| Time, min | Mode | Speed, RPM | Torque, lb*ft | Coolant Out, °F | Oil Galley, °F |
|---|---|---|---|---|---|
| 1 | Cyclic | 750 | 0 | 195 | 210 |
| 10 | Cyclic | 1400 | 180 | 190 | 200 |
| 10 | Cyclic | 1900 | 175 | 190 | 200 |
| 10 | Cyclic | 2400 | 160 | 190 | 205 |
| 5 | Cyclic | 2400 | 320 | 190 | 210 |
| 5 | Cyclic | 1900 | 350 | 190 | 210 |
| 5 | Cyclic | 1400 | 375 | 190 | 205 |
| 3 | Cyclic | 1400 | 755 | 190 | 205 |
| 3 | Cyclic | 1900 | 750 | 190 | 210 |
| 3 | Cyclic | 2400 | 665 | 190 | 215 |

## PRE-TEST ENGINE PERFORMANCE CHECK

After completion of engine run-in, a full load powercurve was completed from 1000 rpm to rated engine speed (2400 rpm) to determine pre-test engine performance. Powercurves were completed using both base JP-8 and JP-8 FRF. The pre-test engine performance check was completed using the same oil change used during the engine run-in segment. Powercurve plots can be seen in the Engine Performance Curves section.

## TEST CYCLE

The test cycle followed during oil evaluation was the standard 210 hr Tactical Wheeled Vehicle cycle as outlined in CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test. The test cycle consists of cyclic modes alternating between 2 hr rated speed conditions and 1 hr idle soaks. Total daily run-time was 14 hrs, 10 hrs at rated, and 4 hrs at idle, with a 10 hr soak overnight before resuming the next day testing. Engine oil and coolant temperatures were elevated to simulate conditions consistent with desert warfare use. Engine operating parameters were controlled throughout testing as specified in Table C2. (Note – The CAT C7 has an integral oil cooler built into the engine block that is cooled by the engine coolant. Due to this, the oil sump temperature of the CAT C7 engine cannot directly be controlled. To achieve the desired oil sump temperature, the water jacket temperature was modified to achieve the oil sump target.) Engine coolant was a 60/40 blend of ethylene glycol antifreeze and deionized water.

**Table C2 - Test Cycle Operating Parameters**

| Parameter | Rated Speed | Idle |
|---|---|---|
| Engine Speed, RPM | 2400 +/- 25 | 750 +/- 25 |
| Water Jacket Out, °F | 223.5 +/- 3 | 110 +/- 3 |
| Oil Sump, °F | 260* | 130* |
| *Oil sump temperature is not controlled. Water jacket temperature is manipulated to achieve desired sump temperature | | |

## OIL SAMPLING

Four ounces of engine oil was sampled every 14 hrs for used oil analysis. Engine oil analysis consisted of the following tests: (Note – at every 70 hr interval, two additional tests were completed on the used oil as shown in Table C3). All oil samples were weighed and logged to take into account during calculations of total engine oil consumption for the test duration.

**Table C3 - Used Oil Analysis Procedures**

| *Every 14hrs* | | |
|---|---|---|
| **ASTM** | **D4739** | Total Base Number |
| **ASTM** | **D664** | Total Acid Number |
| **ASTM** | **D445** | Kinematic Viscosity @ 100°C |
| **ASTM** | **API Gravity** | API Gravity |
| **ASTM** | **D4052** | Density |
| **ASTM** | **TGA SOOT** | TGA Soot |
| **ASTM** | **E168** | Oxidation |
| **ASTM** | **E168** | Nitration |
| **ASTM** | **D5185** | Wear Metals by ICP |

| *Every 70hrs* | | |
|---|---|---|
| **ASTM** | **D445** | Kinematic Viscosity @ 40°C |
| **ASTM** | **D2270** | Kinematic Viscosity Index |

Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

## OIL LEVEL CHECKS

Engine oil level was checked daily and replenished as needed to restore oil level to full mark. This process occurred daily after the completion of the 10 hour soak prior to restarting testing the next day. All oil additions were weighed and logged to take into account during calculation of total engine oil consumption for the test duration.

## FUEL SAMPLING

Four ounces of test fuel was sampled every 14 hours for a visual inspection. The purpose of this inspection was to determine any fuel stability problems after being cycled through the engines fuel system. Fuel samples were collected on the engine fuel return line after passing through both the low and high pressure portions of the fuel system. No signs of fuel and water separation were noticed throughout testing.

## POST-TEST ENGINE PERFORMANCE CHECK

After completion of testing, a full load powercurve was completed from 1000 rpm to rated engine speed (2400 rpm) to determine post-test engine performance. The post-test

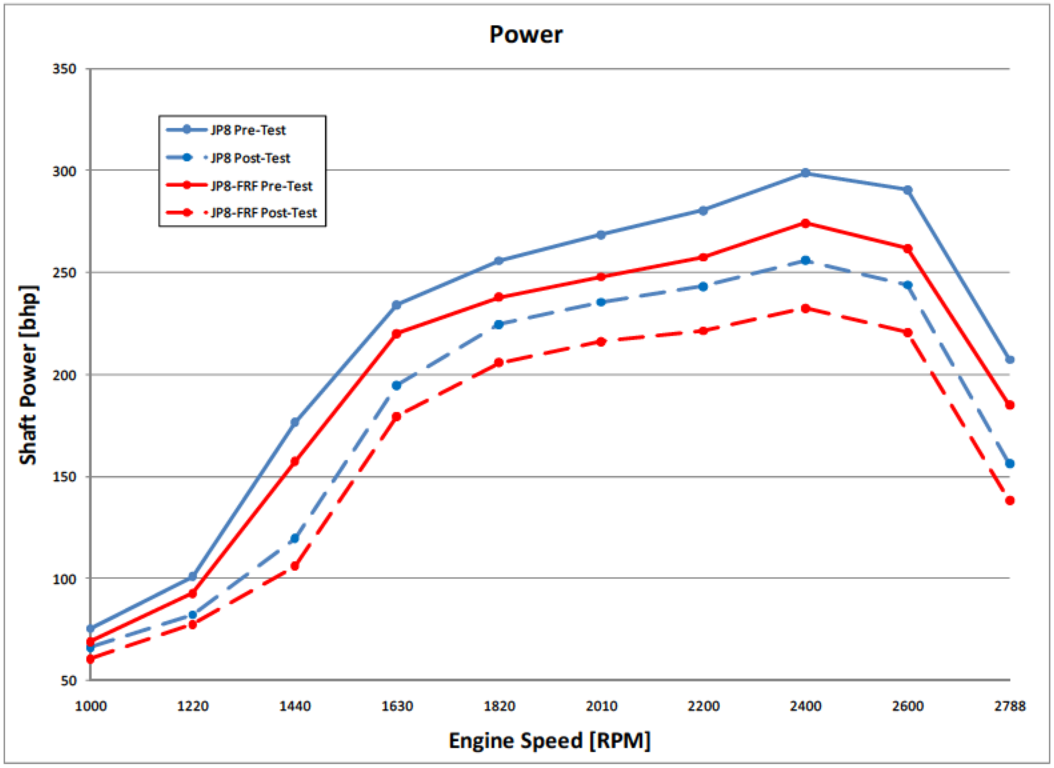
engine performance check was completed using the same oil charge used during the testing segment. Powercurve plots can be seen in the Engine Performance Curves section.

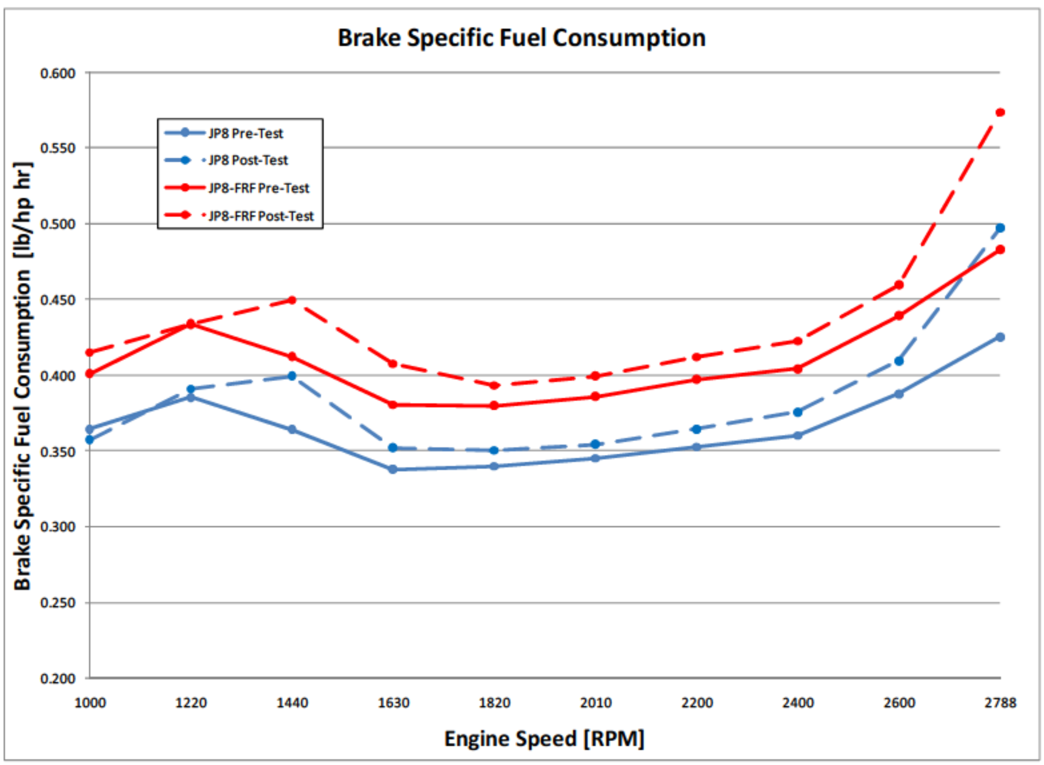
## ENGINE OPERATING CONDITIONS SUMMARY

Below is a summary of the engine operating conditions over the duration of the 210 engine running hours.

| | | **Rated Conditions** *(2400 RPM)* | | **Idle Conditions** *(750 RPM)* | |
|---|---|---|---|---|---|
| **Perameter:** | **Units:** | Average | Std. Dev. | Average | Std. Dev. |
| Engine Speed | *RPM* | 2400.04 | 1.34 | 750.02 | 1.09 |
| Torque* | *ft*lb* | 569.92 | 28.98 | 5.98 | 0.93 |
| Fuel Flow | *lb/hr* | 106.95 | 3.83 | 3.83 | 0.88 |
| Power* | *bhp* | 260.44 | 13.25 | 0.86 | 0.13 |
| BSFC* | *lb/bhp*hr* | 0.411 | 0.008 | 4.619 | 1.642 |
| **Temperatures:** | | | | | |
| Coolant In | *°F* | 209.54 | 1.31 | 100.19 | 3.20 |
| Coolant Out | *°F* | 223.50 | 0.95 | 109.74 | 0.95 |
| Oil Sump | *°F* | 257.08 | 1.17 | 130.39 | 7.27 |
| Fuel In | *°F* | 96.38 | 5.80 | 88.75 | 11.28 |
| Inlet Air | *°F* | 84.87 | 5.27 | 74.82 | 4.90 |
| Intake Manifold Air | *°F* | 140.01 | 0.43 | 73.28 | 5.13 |
| Cylinder 1 Exhaust | *°F* | 888.42 | 14.55 | 182.12 | 4.08 |
| Cylinder 2 Exhaust | *°F* | 1006.03 | 24.04 | 204.75 | 5.02 |
| Cylinder 3 Exhaust | *°F* | 985.99 | 16.17 | 191.48 | 6.61 |
| Cylinder 4 Exhaust | *°F* | 996.45 | 36.15 | 207.91 | 3.28 |
| Cylinder 5 Exhaust | *°F* | 973.96 | 25.69 | 197.34 | 5.13 |
| Cylinder 6 Exhaust | *°F* | 921.37 | 40.06 | 200.37 | 3.42 |
| Exhaust Before Turbo, Front | *°F* | 1034.75 | 19.55 | 207.08 | 5.94 |
| Exhaust Before Turbo, Rear | *°F* | 1040.45 | 28.27 | 217.47 | 4.02 |
| Exhaust After Turbo | *°F* | 774.12 | 18.67 | 208.21 | 9.10 |
| **Pressures:** | | | | | |
| Oil Galley | *psi* | 47.10 | 0.96 | 55.77 | 4.00 |
| Ambient Pressure | *psiA* | 14.38 | 0.09 | 14.36 | 0.09 |
| Intake Before Compressor | *psiA* | 13.63 | 0.16 | 14.28 | 0.09 |
| Intake After Compressor | *psiA* | 42.08 | 0.83 | 14.57 | 0.18 |
| Boost | *psi* | 28.45 | 0.91 | 0.29 | 0.09 |
| Exahust Stack | *psi* | 0.19 | 0.04 | -0.24 | 0.01 |

## ENGINE PERFORMANCE CURVES

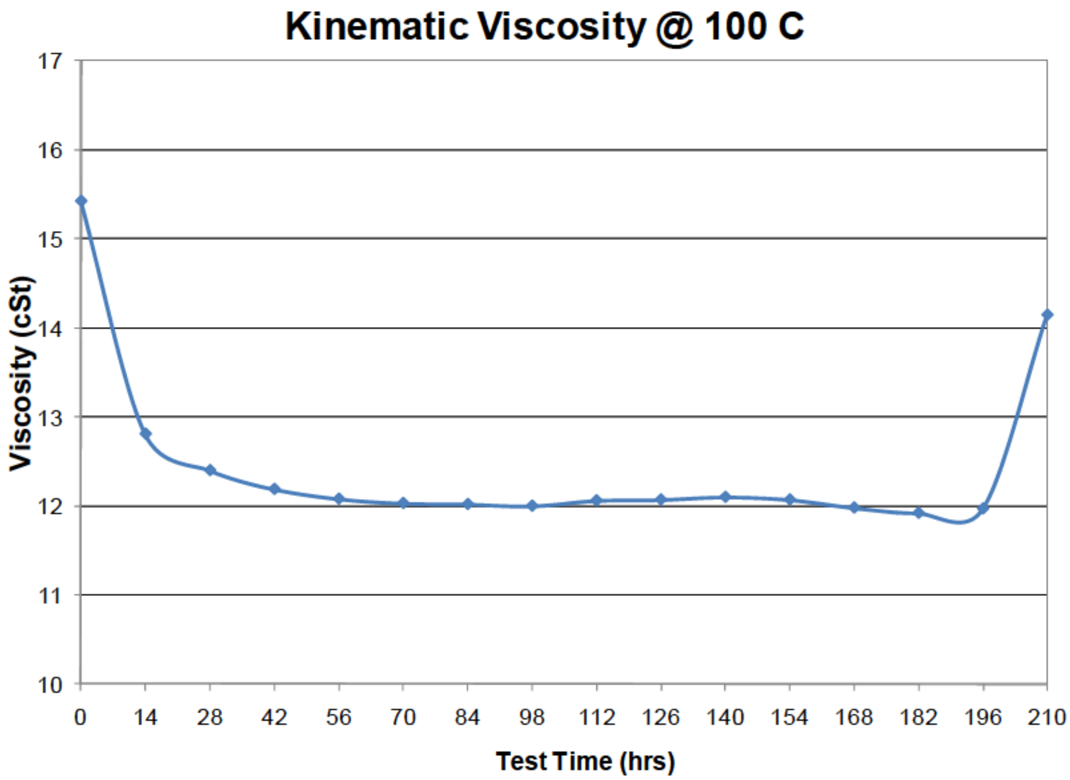


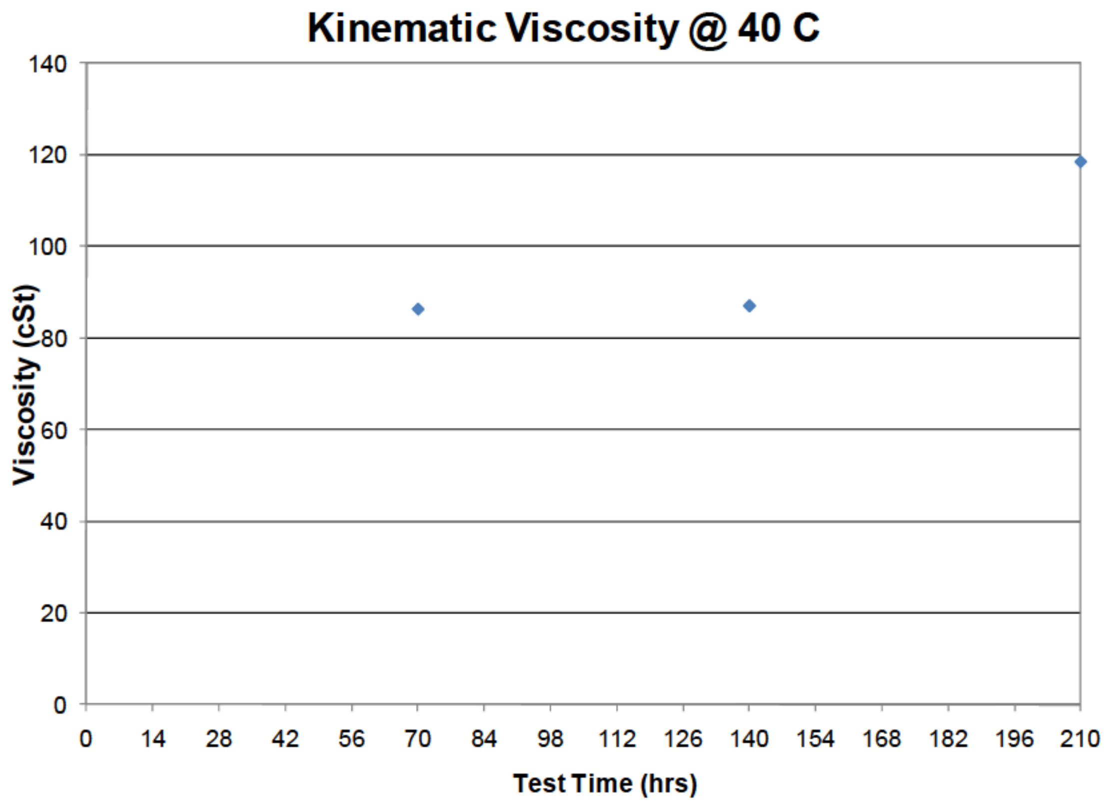



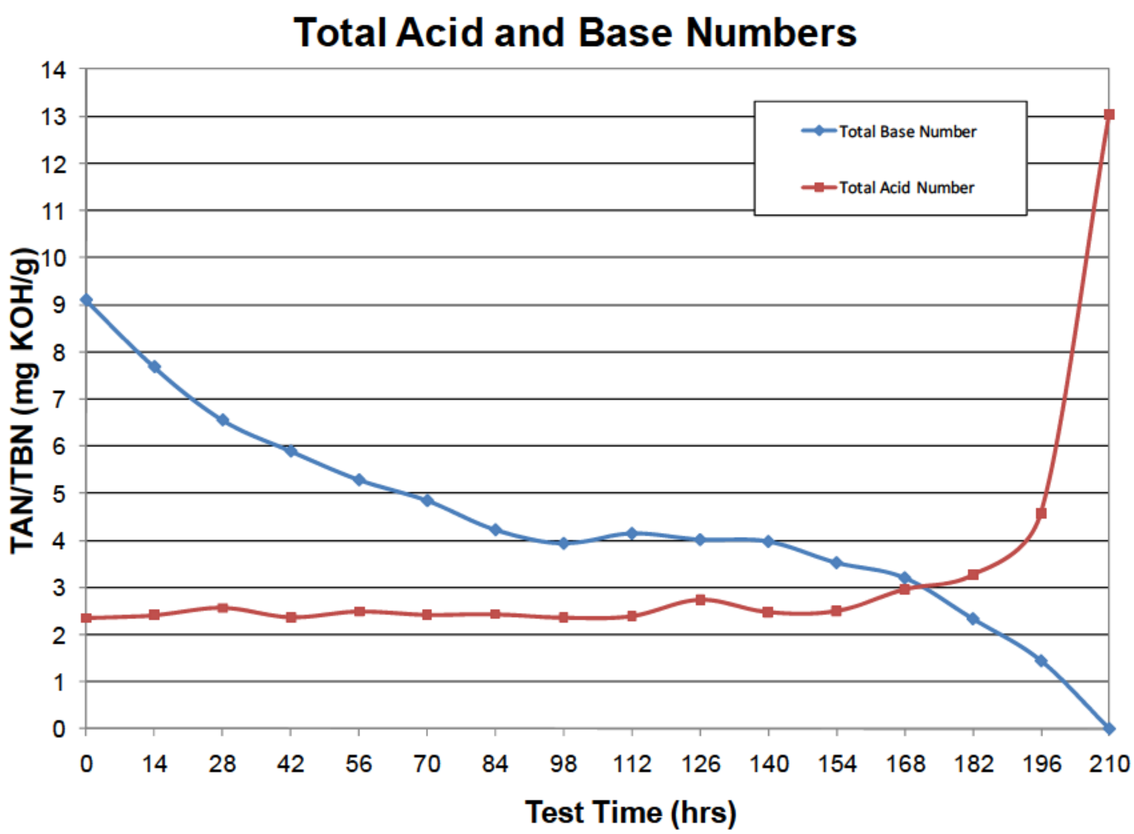
## ENGINE OIL ANALYSIS

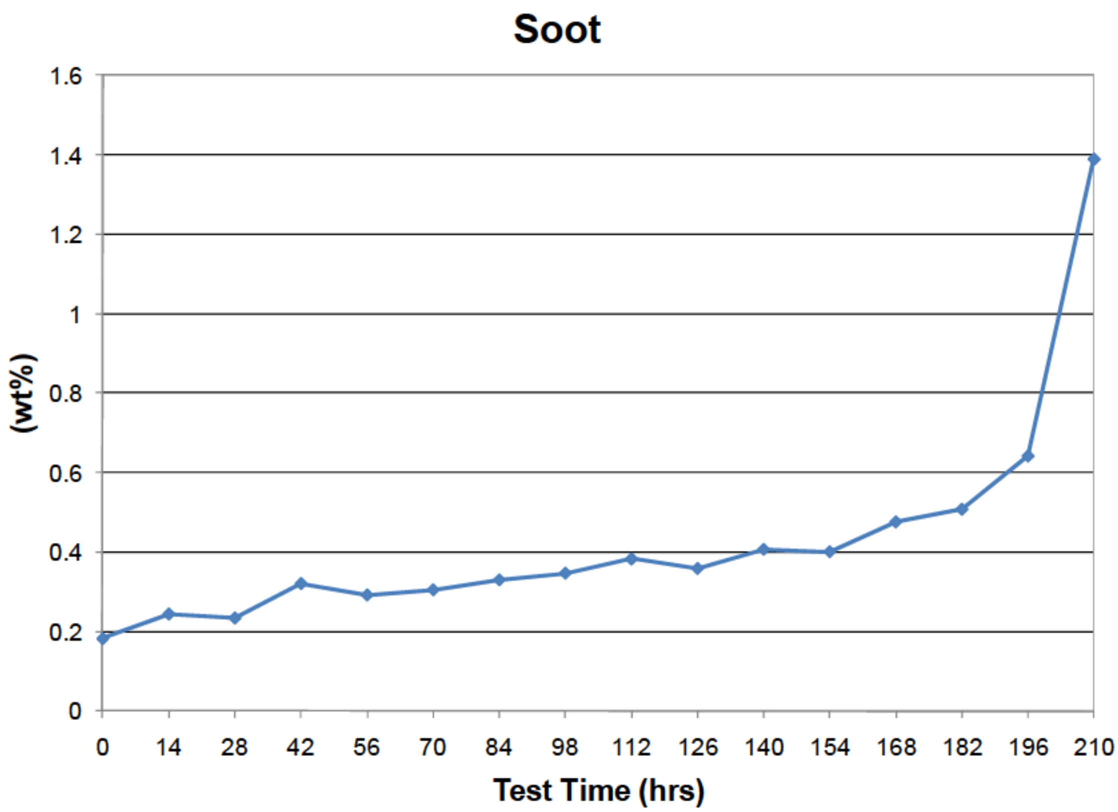
| Property | ASTM Test | Test Hours | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 14 | 28 | 42 | 56 | 70 | 84 | 98 | 112 | 126 | 140 | 154 | 168 | 182 | 196 | 210 |
| Density (g/mL) | D4052 | 0.8724 | 0.8727 | 0.8731 | 0.8736 | 0.8739 | 0.8742 | 0.8746 | 0.8749 | 0.875 | 0.8753 | 0.8756 | 0.876 | 0.8773 | 0.8789 | 0.8833 | 0.9059 |
| Viscosity @ 100°C (cSt) | D445 | 15.43 | 12.81 | 12.4 | 12.19 | 12.08 | 12.03 | 12.02 | 12 | 12.06 | 12.07 | 12.1 | 12.07 | 11.98 | 11.92 | 11.97 | 14.15 |
| Viscosity @ 40°C (cSt) | D445 | | | | | | 86.32 | | | | | 87.02 | | | | | 118.44 |
| Viscosity Index (dyne/cm) | D2270 | | | | | | 133 | | | | | 133 | | | | | 119 |
| Total Base Number (mg KOH/g) | D4739 | 9.1 | 7.68 | 6.55 | 5.89 | 5.28 | 4.84 | 4.22 | 3.93 | 4.14 | 4.01 | 3.97 | 3.52 | 3.2 | 2.33 | 1.44 | <0.05 |
| Total Acid Number (mg KOH/g) | D664 | 2.35 | 2.41 | 2.57 | 2.37 | 2.49 | 2.42 | 2.43 | 2.36 | 2.39 | 2.74 | 2.48 | 2.5 | 2.96 | 3.27 | 4.57 | 13.03 |
| Oxidation (Abs./cm) | E168 FTNG | | 0.09 | 1.36 | 2.66 | 3.91 | 4.81 | 6.02 | 7.22 | 7.59 | 8.61 | 9.44 | 10.93 | 16.67 | 25 | 42.87 | 155.28 |
| Nitration (Abs./cm) | E168 FTNG | | 0.09 | 0 | 0 | 0 | 0.19 | 0 | 0 | 0 | 0 | 0.09 | 0.09 | 1.39 | 3.15 | 7.31 | 9.91 |
| Soot | Soot | 0.182 | 0.244 | 0.234 | 0.321 | 0.292 | 0.305 | 0.33 | 0.347 | 0.383 | 0.359 | 0.407 | 0.401 | 0.476 | 0.508 | 0.642 | 1.39 |
| Wear Metals (ppm) | D5185 | | | | | | | | | | | | | | | | |
| Al | | <1 | 3 | 4 | 9 | 14 | 19 | 20 | 22 | 21 | 20 | 21 | 20 | 22 | 22 | 22 | 22 |
| Sb | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Ba | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| B | | 4 | 2 | 2 | <1 | <1 | 1 | 2 | 2 | 2 | 4 | 1 | 1 | 4 | 2 | 2 | 2 |
| Ca | | 2984 | 2996 | 3032 | 3055 | 3097 | 3073 | 3081 | 3140 | 3129 | 3147 | 3205 | 3237 | 3207 | 3284 | 3311 | 3277 |
| Cr | | <1 | <1 | <1 | <1 | 1 | <1 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 4 |
| Cu | | <1 | 5 | 7 | 9 | 10 | 12 | 14 | 15 | 16 | 16 | 17 | 19 | 21 | 22 | 26 | 96 |
| Fe | | 2 | 12 | 17 | 23 | 29 | 33 | 36 | 39 | 40 | 47 | 55 | 65 | 71 | 76 | 80 | 88 |
| Pb | | 1 | <1 | <1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 10 | 63 |
| Mg | | 10 | 10 | 9 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 13 | 10 | 10 | 12 | 11 |
| Mn | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | 1 | 1 | 1 | 3 |
| Mo | | 2 | 1 | <1 | <1 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 2 |
| Ni | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| P | | 1182 | 1133 | 1108 | 1076 | 1076 | 1044 | 1041 | 1030 | 1027 | 1038 | 1050 | 1031 | 1038 | 1036 | 1063 | 1055 |
| Si | | 6 | 4 | 5 | 6 | 7 | 7 | 8 | 8 | 8 | 8 | 9 | 9 | 10 | 10 | 10 | 11 |
| Ag | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Na | | <5 | <5 | 7 | <5 | 5 | 6 | 6 | 5 | 8 | 6 | 6 | 7 | 6 | 5 | 5 | 5 |
| Sn | | <1 | <1 | <1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 |
| Zn | | 1342 | 1323 | 1316 | 1301 | 1308 | 1285 | 1291 | 1255 | 1321 | 1312 | 1287 | 1325 | 1307 | 1326 | 1343 | 1396 |
| K | | 5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 | <5 |
| Sr | | 1 | 1 | <1 | 1 | <1 | <1 | 1 | <1 | 1 | <1 | <1 | <1 | <1 | <1 | 1 | 1 |
| V | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Ti | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Cd | | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |

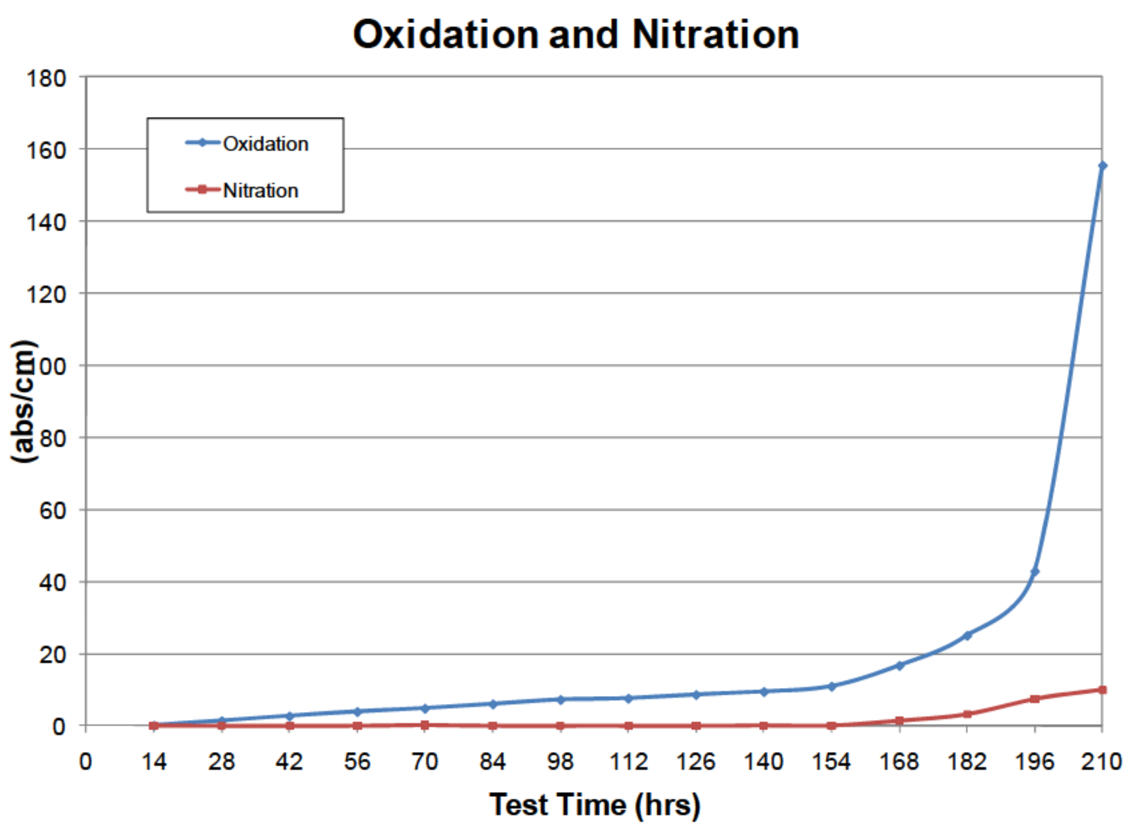
## ENGINE OIL ANALYSIS TRENDS

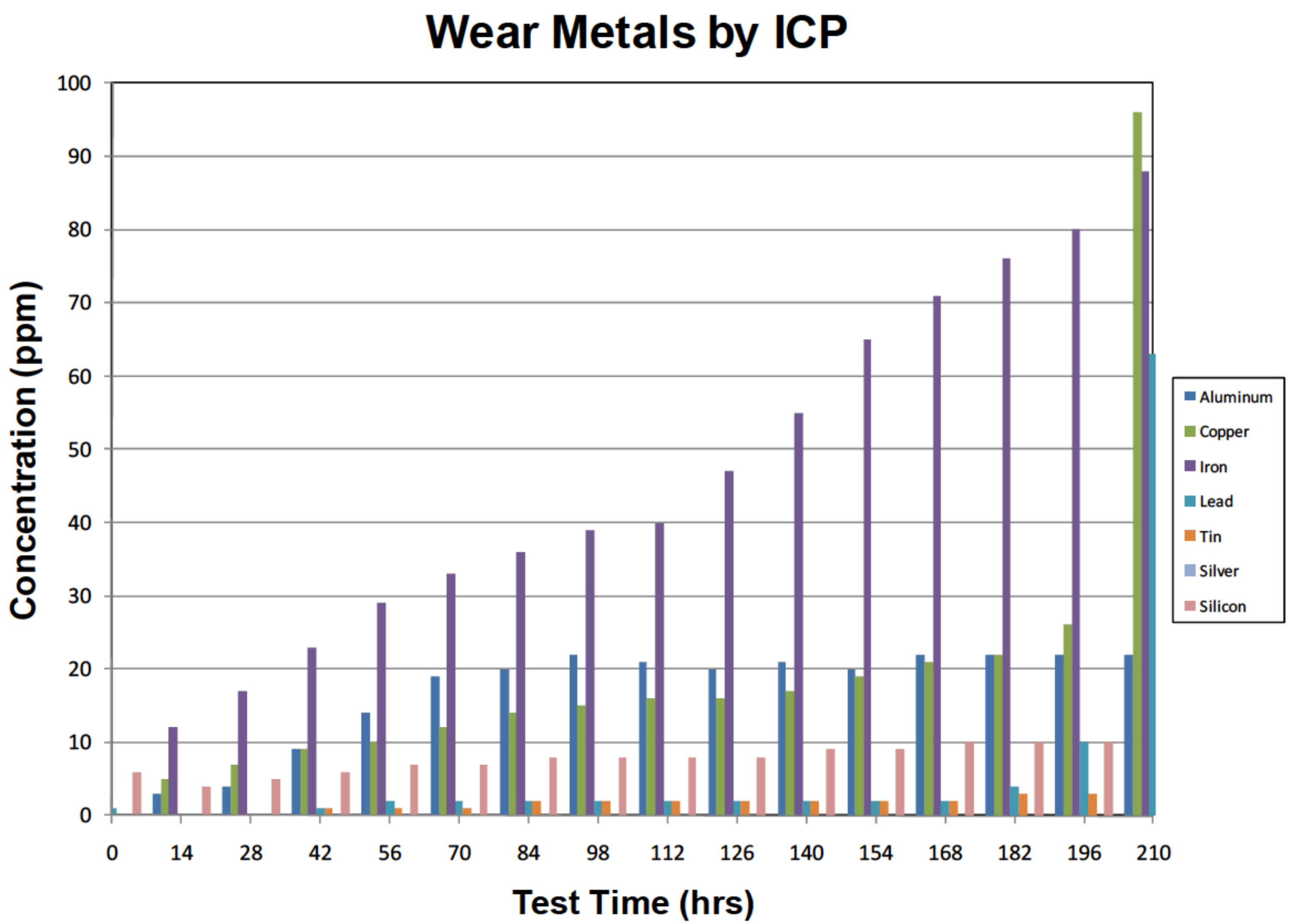



Kinematic Viscosity @ 40 C
Viscosity (cSt)
0
20
40
60
80
100
120
140
0
14
28
42
56
70
84
98
112
126
140
154
168
182
196
210
Test Time (hrs)


Total Acid and Base Numbers
TAN/TBN (mg KOH/g)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Total Base Number
Total Acid Number
0
14
28
42
56
70
84
98
112
126
140
154
168
182
196
210
Test Time (hrs)


Soot
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
(wt%)
0
14
28
42
56
70
84
98
112
126
140
154
168
182
196
210
Test Time (hrs)


Oxidation and Nitration
180
160
140
120
100
80
60
40
20
0
(abs/cm)
Oxidation
Nitration
0
14
28
42
56
70
84
98
112
126
140
154
168
182
196
210
Test Time (hrs)


Wear Metals by ICP
Concentration (ppm)
0
10
20
30
40
50
60
70
80
90
100
0
14
28
42
56
70
84
98
112
126
140
154
168
182
196
210
Test Time (hrs)
Aluminum
Copper
Iron
Lead
Tin
Silver
Silicon

## OIL CONSUMPTION DATA

Average oil consumption per test hour was 0.023 lbs/hr.

| | Additions (lbs) | Samples (lbs) | Consumption (lbs) | Cosumption Accumulated |
|---|---|---|---|---|
| **14-hr** | 0 | 0.32 | -0.32 | -0.32 |
| **28-hr** | 0 | 0.3 | -0.3 | -0.62 |
| **42-hr** | 0 | 0.33 | -0.33 | -0.95 |
| **56-hr** | 0 | 0.33 | -0.33 | -1.28 |
| **70-hr** | 0.77 | 0.3 | 0.47 | -0.81 |
| **84-hr** | 0.77 | 0.29 | 0.48 | -0.33 |
| **98-hr** | 2.37 | 0.27 | 2.1 | 1.77 |
| **112-hr** | 1.83 | 0.28 | 1.55 | 3.32 |
| **126-hr** | 1.1 | 0.28 | 0.82 | 4.14 |
| **140-hr** | 0.72 | 0.28 | 0.44 | 4.58 |
| **154-hr** | 1.28 | 0.28 | 1 | 5.58 |
| **168-hr** | 1.33 | 0.23 | 1.1 | 6.68 |
| **182-hr** | 1.47 | 0.27 | 1.2 | 7.88 |
| **196-hr** | 1.44 | 0.25 | 1.19 | 9.07 |
| **210-hr** | 1.33 | 0.3 | 1.03 | 10.1 |

| | | | |
|---|---|---|---|
| **Initial Fill** | 35.98 | **Total Additions** | 14.41 |
| **EOT Drain** | 31.9 | **Total Samples** | 4.31 |

| | |
|---|---|
| (Initial Fill + Additions) | 50.39 |
| (EOT Drain + Samples) | 36.21 |
| **Total Oil Consumption** | 14.18 |

## LIST OF ENGINE SHUTDOWNS AND CORRECTIVE ACTION

| TOD | Shutdown Failure | Corrective Action |
|---|---|---|
| 1/27/2010 08:10 | Requested Shutdown | Test fuel showed low water content, fuel re-blended with more water, test restarted 02/02/10 |

## POST TEST ENGINE RATINGS

| Ratings | Clyinder Number | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg |
| **Ring Sticking** | | | | | | | |
| Ring No.1 | No | No | No | No | No | No | -- |
| Ring No.2 | No | No | No | No | No | No | -- |
| Ring No.3 | No | No | No | No | No | No | -- |
| **Scuffing % Area** | | | | | | | |
| Ring No.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| Ring No.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| Ring No.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| Piston Crown | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| Piston Skirt | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| Cylinder Liner, % | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| **Piston Carbon, Demerits** | | | | | | | |
| No.1 Groove | 33.50 | 29.50 | 26.50 | 39.00 | 33.75 | 28.25 | 31.75 |
| No.2 Groove | 0.50 | 2.75 | 1.75 | 2.75 | 1.75 | 16.75 | 4.38 |
| No.3 Groove | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| No.1 Land | 34.25 | 25.00 | 31.50 | 28.50 | 27.50 | 26.50 | 28.88 |
| No.2 Land | 17.50 | 21.75 | 20.25 | 29.00 | 14.25 | 50.50 | 25.54 |
| No.3 Land | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| No.4 Land | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Piston Lacquer, Demerits** | | | | | | | |
| No.1 Groove | 0.10 | 0.25 | 0.20 | 0.00 | 0.12 | 0.10 | 0.13 |
| No.2 Groove | 2.81 | 3.06 | 2.65 | 2.87 | 2.15 | 0.74 | 2.38 |
| No.3 Groove | 2.57 | 2.00 | 2.56 | 2.18 | 2.14 | 4.13 | 2.60 |
| No.1 Land | 0.11 | 0.00 | 0.16 | 0.50 | 0.02 | 0.00 | 0.13 |
| No.2 Land | 1.37 | 0.73 | 0.50 | 0.46 | 0.98 | 0.57 | 0.77 |
| No.3 Land | 2.89 | 3.15 | 2.53 | 4.22 | 2.22 | 4.59 | 3.27 |
| No.4 Land | 1.23 | 1.10 | 1.50 | 1.80 | 1.20 | 2.42 | 1.54 |
| Under Crown | 1.50 | 1.50 | 1.64 | 1.80 | 1.50 | 1.80 | 1.62 |
| **Total, Demerits** | 98.33 | 90.79 | 91.74 | 113.08 | 87.58 | 136.35 | 102.98 |
| | | | | | | | |
| **Miscellanous** | | | | | | | |
| Top Groove Fill, % | 19 | 13 | 11 | 22 | 17 | 14 | 16.00 |
| Intermediate Groove Fill, % | 0 | 0 | 0 | 0 | 0 | 6 | 1.00 |
| Top Land Heavy Carbon, % | 13 | 0 | 31.5 | 5 | 4 | 2 | 9.25 |
| Top Land Flaked Carbon, % | 1 | 0 | 2 | 1 | 0 | 0 | 0.67 |
| | | | | | | | |
| **Valve Tulip Deposits, Merits** | | | | | | | |
| Exahust | 8.8 | 9.0 | 8.9 | 8.9 | 9.0 | 9.0 | 8.93 |
| Intake, Front | 9.5 | 9.8 | 9.5 | 9.7 | 9.6 | 9.7 | 9.63 |
| Intake, Rear | 9.5 | 9.9 | 9.6 | 9.8 | 9.6 | 9.7 | 9.68 |
| Intake, Average | 9.5 | 9.9 | 9.6 | 9.8 | 9.6 | 9.7 | 9.66 |

## ENGINE MEASUREMENT CHANGES

### *ENGINE REBUILD MEASUREMENTS, INCHES*

| | Minimum | Maximum | Average | Spec: |
|---|---|---|---|---|
| **Cylinder Bore** | | | | |
| Inside Diameter | 4.3323 | 4.3328 | 4.3326 | 4.3307"-4.3327" |
| Out of Round | 0.0001 | 0.0024 | 0.0014 | Maximum 0.0010" |
| Taper | 0.0004 | 0.0016 | 0.0009 | |
| **Piston Skirt Diameter** | 4.3271 | 4.3277 | 4.3273 | |
| Piston Skirt to Cylinder Bore Clearance | 0.0046 | 0.0057 | 0.0053 | 0.0020"-0.0050" |
| **Piston Ring End Gaps** | | | | |
| Top Ring | 0.018 | 0.019 | 0.018 | |
| Second Ring | 0.050 | 0.050 | 0.050 | |
| Oil Control Ring | 0.016 | 0.018 | 0.018 | |
| **Ring To Groove Clearance** | | | | |
| Second Ring | 0.002 | 0.002 | 0.002 | |
| Oil Control Ring | 0.002 | 0.002 | 0.002 | |
| **Bearing Clearances** | | | | |
| Connecting Rod to Journal | 0.0030 | 0.0030 | 0.0030 | 0.0021"-0.0061" |
| Main Bearing to Journa | 0.0035 | 0.0040 | 0.0037 | 0.0028"-0.0068" |

## *PRE-TEST CYLINDER BORE MEASUREMENTS, INCHES*

| **Cylinder** | Depth | Tranverse (TD) | Longitude (LD) | Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2 | Out of Round |
|---|---|---|---|---|---|
| **1** | Top | 4.3319 | 4.3308 | | 0.0011 |
| | Middle | 4.3324 | 4.3314 | 4.3323 | 0.0010 |
| | Bottom | 4.3321 | 4.3322 | | 0.0001 |
| | Taper | 0.0005 | 0.0014 | | |
| **2** | Top | 4.3328 | 4.3304 | | 0.0024 |
| | Middle | 4.3330 | 4.3309 | 4.3327 | 0.0021 |
| | Bottom | 4.3324 | 4.3318 | | 0.0006 |
| | Taper | 0.0006 | 0.0014 | | |
| **3** | Top | 4.3326 | 4.3306 | | 0.0020 |
| | Middle | 4.3329 | 4.3309 | 4.3326 | 0.0020 |
| | Bottom | 4.3323 | 4.3317 | | 0.0006 |
| | Taper | 0.0006 | 0.0011 | | |
| **4** | Top | 4.3327 | 4.3304 | | 0.0023 |
| | Middle | 4.3331 | 4.3309 | 4.3328 | 0.0022 |
| | Bottom | 4.3325 | 4.3317 | | 0.0008 |
| | Taper | 0.0006 | 0.0013 | | |
| **5** | Top | 4.3324 | 4.3306 | | 0.0018 |
| | Middle | 4.3330 | 4.3310 | 4.3327 | 0.0020 |
| | Bottom | 4.3324 | 4.3317 | | 0.0007 |
| | Taper | 0.0006 | 0.0011 | | |
| **6** | Top | 4.3323 | 4.3303 | | 0.0020 |
| | Middle | 4.3326 | 4.3312 | 4.3324 | 0.0014 |
| | Bottom | 4.3322 | 4.3319 | | 0.0003 |
| | Taper | 0.0004 | 0.0016 | | |

## *POST-TEST CYLINDER BORE MEASUREMENTS, IN*

| **Cylinder** | Depth | Tranverse (TD) | Longitude (LD) | Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2 | Out of Round |
|---|---|---|---|---|---|
| **1** | Top | 4.3324 | 4.3317 | | 0.0007 |
| | Middle | 4.3323 | 4.3314 | 4.3318 | 0.0009 |
| | Bottom | 4.3313 | 4.3316 | | 0.0003 |
| | Taper | 0.0011 | 0.0003 | | |
| **2** | Top | 4.3324 | 4.3315 | | 0.0009 |
| | Middle | 4.3323 | 4.3310 | 4.3318 | 0.0013 |
| | Bottom | 4.3312 | 4.3314 | | 0.0002 |
| | Taper | 0.0012 | 0.0005 | | |
| **3** | Top | 4.3324 | 4.3312 | | 0.0012 |
| | Middle | 4.3324 | 4.3310 | 4.3319 | 0.0014 |
| | Bottom | 4.3314 | 4.3312 | | 0.0002 |
| | Taper | 0.0010 | 0.0002 | | |
| **4** | Top | 4.3324 | 4.3312 | | 0.0012 |
| | Middle | 4.3324 | 4.3310 | 4.3319 | 0.0014 |
| | Bottom | 4.3314 | 4.3313 | | 0.0001 |
| | Taper | 0.0010 | 0.0003 | | |
| **5** | Top | 4.3325 | 4.3310 | | 0.0015 |
| | Middle | 4.3324 | 4.3310 | 4.3319 | 0.0014 |
| | Bottom | 4.3314 | 4.3313 | | 0.0001 |
| | Taper | 0.0011 | 0.0003 | | |
| **6** | Top | 4.3324 | 4.3318 | | 0.0006 |
| | Middle | 4.3323 | 4.3315 | 4.3318 | 0.0008 |
| | Bottom | 4.3312 | 4.3316 | | 0.0004 |
| | Taper | 0.0012 | 0.0003 | | |

***CYLINDER BORE DIAMETER CHANGES, IN***

| Cylinder | Depth | Tranverse (TD) | Longitude (LD) | Avg Bore Dia. Change (TD@MID + TD@BOT)/2 |
|---|---|---|---|---|
| **1** | Top | 0.0005 | 0.0009 | |
| | Middle | 0.0001 | 0.0000 | 0.0004 |
| | Bottom | 0.0008 | 0.0006 | |
| | | | | |
| **2** | Top | 0.0004 | 0.0011 | |
| | Middle | 0.0007 | 0.0001 | 0.0010 |
| | Bottom | 0.0012 | 0.0004 | |
| | | | | |
| **3** | Top | 0.0002 | 0.0006 | |
| | Middle | 0.0005 | 0.0001 | 0.0007 |
| | Bottom | 0.0009 | 0.0005 | |
| | | | | |
| **4** | Top | 0.0003 | 0.0008 | |
| | Middle | 0.0007 | 0.0001 | 0.0009 |
| | Bottom | 0.0011 | 0.0004 | |
| | | | | |
| **5** | Top | 0.0001 | 0.0004 | |
| | Middle | 0.0006 | 0.0000 | 0.0008 |
| | Bottom | 0.0010 | 0.0004 | |
| | | | | |
| **6** | Top | 0.0001 | 0.0015 | |
| | Middle | 0.0003 | 0.0003 | 0.0007 |
| | Bottom | 0.0010 | 0.0003 | |
| | | | | |
| **Avgerage All Cylinders** | Top | 0.0003 | 0.0009 | |
| | Middle | 0.0005 | 0.0001 | |
| | Bottom | 0.0010 | 0.0004 | |
| | | | | |

## *PISTON SKIRT TO BORE CLEARANCE, IN*

| | Cylinder | Average Bore Diameter | Piston Skirt Diameter | Clearance |
|---|---|---|---|---|
| Pre - Test | 1 | 4.3323 | 4.3277 | 0.0046 |
| | 2 | 4.3327 | 4.3272 | 0.0055 |
| | 3 | 4.3326 | 4.3271 | 0.0055 |
| | 4 | 4.3328 | 4.3271 | 0.0057 |
| | 5 | 4.3327 | 4.3274 | 0.0053 |
| | 6 | 4.3324 | 4.3273 | 0.0051 |
| | | | | |
| Post - Test | 1 | 4.3318 | 4.3277 | 0.0041 |
| | 2 | 4.3318 | 4.3272 | 0.0045 |
| | 3 | 4.3319 | 4.3271 | 0.0048 |
| | 4 | 4.3319 | 4.3270 | 0.0049 |
| | 5 | 4.3319 | 4.3273 | 0.0046 |
| | 6 | 4.3318 | 4.3273 | 0.0044 |

## *TOP AND SECOND RING RADIAL WEAR, IN*

| Top Ring | | | | |
|---|---|---|---|---|
| Cylinder | Position | Before | After | Delta |
| 1 | 1 | 0.17350 | 0.17350 | 0.00000 |
| | 2 | 0.17180 | 0.17180 | 0.00000 |
| | 3 | 0.17335 | 0.17325 | 0.00010 |
| | 4 | 0.17355 | 0.17355 | 0.00000 |
| | 5 | 0.17405 | 0.17400 | 0.00005 |
| 2 | 1 | 0.17380 | 0.17380 | 0.00000 |
| | 2 | 0.17125 | 0.17120 | 0.00005 |
| | 3 | 0.17215 | 0.17210 | 0.00005 |
| | 4 | 0.17225 | 0.17225 | 0.00000 |
| | 5 | 0.17360 | 0.17345 | 0.00015 |
| 3 | 1 | 0.17255 | 0.17255 | 0.00000 |
| | 2 | 0.17065 | 0.17060 | 0.00005 |
| | 3 | 0.17270 | 0.17270 | 0.00000 |
| | 4 | 0.17260 | 0.17255 | 0.00005 |
| | 5 | 0.17210 | 0.17200 | 0.00010 |
| 4 | 1 | 0.17480 | 0.17480 | 0.00000 |
| | 2 | 0.17390 | 0.17370 | 0.00020 |
| | 3 | 0.17190 | 0.17190 | 0.00000 |
| | 4 | 0.17260 | 0.17255 | 0.00005 |
| | 5 | 0.17410 | 0.17410 | 0.00000 |
| 5 | 1 | 0.17385 | 0.17385 | 0.00000 |
| | 2 | 0.17365 | 0.17360 | 0.00005 |
| | 3 | 0.17435 | 0.17425 | 0.00010 |
| | 4 | 0.17245 | 0.17235 | 0.00010 |
| | 5 | 0.17385 | 0.17325 | 0.00060 |
| 6 | 1 | 0.17410 | 0.17405 | 0.00005 |
| | 2 | 0.17210 | 0.17200 | 0.00010 |
| | 3 | 0.17215 | 0.17210 | 0.00005 |
| | 4 | 0.17355 | 0.17355 | 0.00000 |
| | 5 | 0.17375 | 0.17360 | 0.00015 |
| *Note - Measurements with a negitive delta value, shown in italics, are considered pre-test measurements error | | | | |

| | |
|---|---|
| Maximum | 0.00060 |
| Average | 0.00007 |

| Second Ring | | | | |
|---|---|---|---|---|
| Cylinder | Position | Before | After | Delta |
| 1 | 1 | 0.16680 | 0.16680 | 0.00000 |
| | 2 | 0.16720 | 0.16735 | -0.00015 |
| | 3 | 0.16915 | 0.16920 | -0.00005 |
| | 4 | 0.16825 | 0.16815 | 0.00010 |
| | 5 | 0.16725 | 0.16710 | 0.00015 |
| 2 | 1 | 0.16720 | 0.16670 | 0.00050 |
| | 2 | 0.16720 | 0.16705 | 0.00015 |
| | 3 | 0.16910 | 0.16910 | 0.00000 |
| | 4 | 0.16645 | 0.16645 | 0.00000 |
| | 5 | 0.16590 | 0.16595 | -0.00005 |
| 3 | 1 | 0.16785 | 0.16795 | -0.00010 |
| | 2 | 0.16720 | 0.16755 | -0.00035 |
| | 3 | 0.16880 | 0.16885 | -0.00005 |
| | 4 | 0.16900 | 0.16880 | 0.00020 |
| | 5 | 0.16770 | 0.16765 | 0.00005 |
| 4 | 1 | 0.16780 | 0.16765 | 0.00015 |
| | 2 | 0.16745 | 0.16745 | 0.00000 |
| | 3 | 0.16875 | 0.16855 | 0.00020 |
| | 4 | 0.16860 | 0.16840 | 0.00020 |
| | 5 | 0.16775 | 0.16770 | 0.00005 |
| 5 | 1 | 0.16860 | 0.16840 | 0.00020 |
| | 2 | 0.16800 | 0.16805 | -0.00005 |
| | 3 | 0.16820 | 0.16815 | 0.00005 |
| | 4 | 0.16840 | 0.16800 | 0.00040 |
| | 5 | 0.16835 | 0.16835 | 0.00000 |
| 6 | 1 | 0.17135 | 0.17120 | 0.00015 |
| | 2 | 0.16980 | 0.16965 | 0.00015 |
| | 3 | 0.16870 | 0.16865 | 0.00005 |
| | 4 | 0.17135 | 0.17125 | 0.00010 |
| | 5 | 0.17145 | 0.17135 | 0.00010 |
| *Note - Measurements with a negitive delta value, shown in italics, are considered pre-test measurements error | | | | |

| | |
|---|---|
| Maximum | 0.00050 |
| Average | 0.00007 |

***PISTON RING GAP MEASUREMENTS, IN***

| Cylinder | Ring No. | Before | After | Delta |
|---|---|---|---|---|
| 1 | 1 | 0.018 | 0.018 | 0.000 |
| | 2 | 0.050 | 0.050 | 0.000 |
| | 3 | 0.018 | 0.018 | 0.000 |
| 2 | 1 | 0.019 | 0.018 | -0.001 |
| | 2 | 0.050 | 0.050 | 0.000 |
| | 3 | 0.016 | 0.017 | 0.001 |
| 3 | 1 | 0.018 | 0.018 | 0.000 |
| | 2 | 0.050 | 0.050 | 0.000 |
| | 3 | 0.018 | 0.018 | 0.000 |
| 4 | 1 | 0.019 | 0.020 | 0.001 |
| | 2 | 0.050 | 0.050 | 0.000 |
| | 3 | 0.018 | 0.019 | 0.001 |
| 5 | 1 | 0.018 | 0.018 | 0.000 |
| | 2 | 0.050 | 0.050 | 0.000 |
| | 3 | 0.018 | 0.018 | 0.000 |
| 6 | 1 | 0.018 | 0.018 | 0.000 |
| | 2 | 0.050 | 0.050 | 0.000 |
| | 3 | 0.018 | 0.018 | 0.000 |

| | |
|---|---|
| Ring No. 1 max increase | 0.001 |
| Ring No. 2 max increase | 0.000 |
| Ring No. 3 max increase | 0.001 |

| | |
|---|---|
| Ring No. 1 avg increase | 0.000 |
| Ring No. 2 avg increase | 0.000 |
| Ring No. 3 avg increase | 0.000 |

## *PISTON RING MASS, GRAMS*

| Cylinder | Ring No. | Before | After | Delta |
|---|---|---|---|---|
| **1** | 1 | 28.7876 | 28.7829 | 0.0047 |
| | 2 | 26.9954 | 26.9930 | 0.0024 |
| | 3 | 17.2255 | 17.2218 | 0.0037 |
| **2** | 1 | 28.7508 | 28.7468 | 0.0040 |
| | 2 | 26.8918 | 26.8893 | 0.0025 |
| | 3 | 17.0109 | 17.0060 | 0.0049 |
| **3** | 1 | 28.5248 | 28.5216 | 0.0032 |
| | 2 | 27.2362 | 27.2342 | 0.0020 |
| | 3 | 17.2324 | 17.2292 | 0.0032 |
| **4** | 1 | 28.7519 | 28.7480 | 0.0039 |
| | 2 | 27.1907 | 27.1884 | 0.0023 |
| | 3 | 17.2400 | 17.2354 | 0.0046 |
| **5** | 1 | 28.7232 | 28.7171 | 0.0061 |
| | 2 | 26.9948 | 26.9918 | 0.0030 |
| | 3 | 17.0670 | 17.0623 | 0.0047 |
| **6** | 1 | 28.7655 | 28.7635 | 0.0020 |
| | 2 | 27.2083 | 27.2053 | 0.0030 |
| | 3 | 17.1438 | 17.1388 | 0.0050 |

| | |
|---|---|
| Ring No. 1 max decrease | 0.0061 |
| Ring No. 2 max decrease | 0.0030 |
| Ring No. 3 max decrease | 0.0050 |

| | |
|---|---|
| Ring No. 1 avg decrease | 0.0040 |
| Ring No. 2 avg decrease | 0.0025 |
| Ring No. 3 avg decrease | 0.0043 |

## *CONNECTING ROD BEARING WEIGHT LOSS, GRAMS*

| Rod Bearing | Shell | Before | After | Change |
|---|---|---|---|---|
| 1 | Top | 75.3253 | 75.2852 | 0.0401 |
| | Bottom | 75.2259 | 75.2161 | 0.0098 |
| 2 | Top | 75.2758 | 75.2397 | 0.0361 |
| | Bottom | 75.5916 | 75.5815 | 0.0101 |
| 3 | Top | 76.0103 | 75.9405 | 0.0698 |
| | Bottom | 75.6845 | 75.6771 | 0.0074 |
| 4 | Top | 75.5879 | 75.5211 | 0.0668 |
| | Bottom | 75.8830 | 75.8721 | 0.0109 |
| 5 | Top | 75.2964 | 75.1899 | 0.1065 |
| | Bottom | 75.9114 | 75.9012 | 0.0102 |
| 6 | Top | 75.5086 | 75.4086 | 0.1000 |
| | Bottom | 76.0697 | 76.0598 | 0.0099 |

| | |
|---|---|
| Maximum | 0.1065 |
| Average | 0.0398 |

## *MAIN BEARING WEIGHT LOSS, GRAMS*

| Main Bearing | Shell | Before | After | Change |
|---|---|---|---|---|
| 1 | Top | 73.7087 | 73.7055 | 0.0032 |
| | Bottom | 80.6828 | 80.6804 | 0.0024 |
| 2 | Top | 74.0133 | 74.0100 | 0.0033 |
| | Bottom | 80.7708 | 80.7692 | 0.0016 |
| 3 | Top | 73.8819 | 73.8800 | 0.0019 |
| | Bottom | 80.6903 | 80.6893 | 0.0010 |
| 4 | Top | 73.8877 | 73.8867 | 0.0010 |
| | Bottom | 80.7936 | 80.7921 | 0.0015 |
| 5 | Top | 73.8473 | 73.8399 | 0.0074 |
| | Bottom | 80.7905 | 80.7886 | 0.0019 |
| 6 | Top | 142.6498 | 142.6425 | 0.0073 |
| | Bottom | 82.2074 | 82.2048 | 0.0026 |
| 7 | Top | 74.0330 | 74.0300 | 0.0030 |
| | Bottom | 80.8645 | 80.8626 | 0.0019 |

| | |
|---|---|
| Maximum | 0.0074 |
| Average | 0.0029 |

# PHOTOGRAPHS

CAT C7 - Tactical Wheeled Vehicle Cycle

| | | | |
|---|---|---|---|
| Oil Code: | LO-246362 | EOT Date: | 02/19/10 |
| Test No.: | JP8FRF-C71-W-210 | Test Hours: | 210 |

Piston Skirt Thrust - Best Cyl 5

Piston Skirt Anti-thrust - Best Cyl 5

CAT C7 - Tactical Wheeled Vehicle Cycle

| | | | |
|---|---|---|---|
| **Oil Code:** | LO-246362 | **EOT Date:** | 02/19/10 |
| **Test No.:** | JP8FRF-C71-W-210 | **Test Hours:** | 210 |

**Piston Skirt Thrust - Worst Cyl 6**

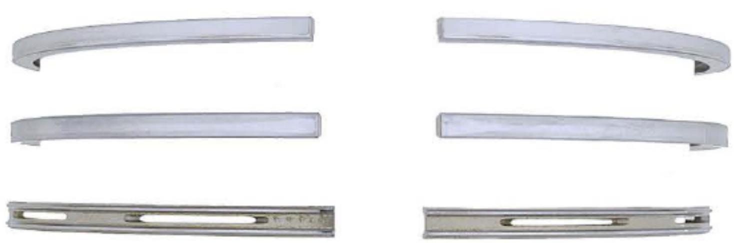
**Piston Skirt Anti-thrust - Worst Cyl 6**

**CAT C7 - Tactical Wheeled Vehicle Cycle**

| | | | |
|---|---|---|---|
| **Oil Code:** | LO-246362 | **EOT Date:** | 02/19/10 |
| **Test No.:** | JP8FRF-C71-W-210 | **Test Hours:** | 210 |

**Piston Rings - Best Cyl 3**

**Piston Rings - Worst Cyl 5**



**CAT C7 - Tactical Wheeled Vehicle Cycle**

| | | | |
|---|---|---|---|
| **Oil Code:** | LO-246362 | **EOT Date:** | 02/19/10 |
| **Test No.:** | JP8FRF-C71-W-210 | **Test Hours:** | 210 |

**Piston Undercrown - Best Cyl 5**

**Piston Undercrown - Worst Cyl 6**

CAT C7 - Tactical Wheeled Vehicle Cycle

| | | | |
|---|---|---|---|
| **Oil Code:** | LO-246362 | **EOT Date:** | 02/19/10 |
| **Test No.:** | JP8FRF-C71-W-210 | **Test Hours:** | 210 |

Engine Block Cylinder Bore - Best Cyl 3

Engine Block Cylinder Bore - Worst Cyl 1

**CAT C7 - Tactical Wheeled Vehicle Cycle**

| | | | |
|---|---|---|---|
| **Oil Code:** | LO-246362 | **EOT Date:** | 02/19/10 |
| **Test No.:** | JP8FRF-C71-W-210 | **Test Hours:** | 210 |

**Intake and Exhaust Valve - Worst Cyl 1**

**CAT C7 - Tactical Wheeled Vehicle Cycle**

| | | | |
|---|---|---|---|
| **Oil Code:** | LO-246362 | **EOT Date:** | 02/19/10 |
| **Test No.:** | JP8FRF-C71-W-210 | **Test Hours:** | 210 |

**Rod Bearings**

**CAT C7 - Tactical Wheeled Vehicle Cycle**

| | | | |
|---|---|---|---|
| **Oil Code:** | LO-246362 | **EOT Date:** | 02/19/10 |
| **Test No.:** | JP8FRF-C71-W-210 | **Test Hours:** | 210 |

**Main Bearings**

**CAT C7 - Tactical Wheeled Vehicle Cycle**

| | | | |
|---|---|---|---|
| **Oil Code:** | LO-246362 | **EOT Date:** | 02/19/10 |
| **Test No.:** | JP8FRF-C71-W-210 | **Test Hours:** | 210 |

**Crossheads - 1,2,3,4,5,6**

# APPENDIX D

## Literature Review Regarding PuriNOx

TFLRF staff reviewed "TxDOT Emulsified Diesel Fuel Final Report," 2004, by Ron Matthews, et al., Report No. FHWA/TX-04/4576-3. This report covers TxDOT experiences using Lubrizol PuriNOx fuel (emulsified fuel containing approximately 20% vol water). The following information was mined from the report:

- Some vehicles powered by 6M 6.5L diesel engines contain an optical sensor to detect water in fuel. The milky appearance of PuriNOx macroemulsion fuel prevented use in GM 6.5L diesel engines with the optical sensor.

- From the cost analysis, a slightly increased rate of fuel injector pump replacements was observed.

- Fuel/water separation leads to increased corrosion in labware tests; when fuel remained fully mixed, no corrosion was observed.

Table D1 shows the fuel consumption effects observed when using PuriNOx. Overall, mechanical fuel injection systems experienced slightly greater power loss than electronic systems on PuriNOx as compared to DF-2.

**Table D1. Fuel Consumption Comparisons**

| | **Engine** | **Injection Type** | **Fuel** | **Consumption (g/hp-hr)** | **% Change** | |
|---|---|---|---|---|---|---|
| | | | ***Heavy Duty Applications*** | | | |
| **Telescoping Boom Excavator** | Cummins ISB-190 | E | 2D - on road | 174.6 | | |
| | | | PuriNOx | 217.1 | -24.4% | |
| | Cummins 6BTA5.9 | M | 2D - on road | 169.2 | | |
| | | | PuriNOx | 227.7 | -31.6% | |
| **Wheeled Loader** | Cummins ISB-190 | E | 2D - on road | 165.8 | | |
| | | | high S off road | 169.8 | **on-road* | **off-road* |
| | | | PuriNOx | 205.3 | -23.8% | -20.9% |
| | Cummins 6BTA5.9 | M | 2D - on road | 163.4 | | |
| | | | low S off road | 170.5 | **on-road* | **off-road* |
| | | | PuriNOx | 211.0 | -29.1% | -23.8% |
| **Average %** | ***mechanical injection*** | | -30.4% | ***electronic injection*** | | -24.1% |
| | | | ***Small Utility Applications, on Road*** | | | |
| | **Engine** | | **Fuel** | **Consumption (g/hp-hr)** | **% Change** | |
| **Mower** | 02 Yanmar 10hp | | 2D | 234.6 | | |
| | | | PuriNOx | 294.9 | -25.7% | |
| **Signal** | 02 Yanmar 10hp | | 2D | 215.9 | | |
| | | | PuriNOx | 279.3 | -29.4% | |
| **Sprayer** | 02 Yanmar 10hp | | 2D | 309.5 | | |
| | | | PuriNOx | 357.0 | -15.4% | |

| | Engine | Injection Type | Fuel | Consumption (g/hp-hr) | % Change | |
|---|---|---|---|---|---|---|
| **TxDOT Single Axle** | Caterpillar 3126B | E | 2D | 6.85 | | |
| | | | PuriNOx | 5.84 | -14.6% | |
| | International T444E | E | 2D | 6.91 | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | PuriNOx | 6.44 | -6.8% | |
| | International 7.6T-I6 | M | 2D | 6.36 | | |
| | | | PuriNOx | 5.68 | -10.8% | |
| | Ford? 1060 | M | 2D | 6.90 | | |
| | | | PuriNOx | 5.80 | -15.9% | |
| **TxDOT Tandem Axle** | 90 Cummins L10-300 | M | 2D | 5.29 | | |
| | | | PuriNOx | 4.53 | -14.3% | |
| | Caterpillar? C10 | E | 2D | 5.00 | | |
| | | | PuriNOx | 4.36 | -12.7% | |
| | 89 Cummins L10-300 | M | 2D | 5.20 | | |
| | | | PuriNOx | 4.63 | -10.9% | |
| | Caterpillar 3176 | E | 2D | 5.04 | | |
| | | | PuriNOx | 4.66 | -7.4% | |
| **Average %** | ***mechanical injection**** | | -13.3% | ***electronic injection***** | | -11.6% |
| **Does not include L10-300 - **Does not include T444E* | | | | | | |

APPENDIX E

# TESTING IN PICKUP [6.5L(T)(E) ENGINE]

Wide-open throttle (WOT) accelerations were conducted to obtain quantitative estimates of the change in vehicle performance when converting from different base fuels and corresponding blends.

A 1996 ¾-ton Chevrolet pickup truck powered by a 6.5L AM General turbo-charged diesel engine was used to conduct the testing.

WOT accelerations were conducted using the following fuels:

a. Certification Ultra Low Sulfur Diesel (ULSD)
b. Aviation Turbine Fuel, JP-8
c. Designated blend of Fire Resistant Fuel consisting of JP-8, surfactant and 10% vol water
d. Designated blend of Fire Resistant Fuel consisting of Diesel, surfactant and water

WOT acceleration tests were conducted at the SWRI test track located at the NW quadrant of the institute. Only the north side of the track was used to conduct the acceleration tests at all designated speeds.

Procedures for conducting the acceleration tests were as follows:

a. Engine was operated at normal speeds of 30–35 mph for five laps around the track prior to the acceleration tests.

b. From a standing start with engine at idle (braked if necessary), and the transmission in high range, the vehicle was accelerated at wide-open throttle to the speeds specified in the test data sheet (0-35) (0-45) (0-55).

c. Six individual runs were performed with each fuel, three in each direction. The time to reach the specified speed was recorded for each run. The vehicle was operated a minimum of two miles at normal operating conditions (approximately 25 percent throttle) after each three acceleration runs to stabilize engine temperature and performance.

Figure E1 shows the acceleration time versus speed for the different fuels and blends with the 95% confidence intervals attached. Summary: the two JP-8 fuels are not significantly different from each other but are significantly different from the ULSD fuels. The two ULSD fuels appear significantly different from each other. The combined difference across all speeds with the neat JP-8 and JP-8 blend were 1.0 % while the combined difference for the neat diesel and diesel blend were 7.6%.

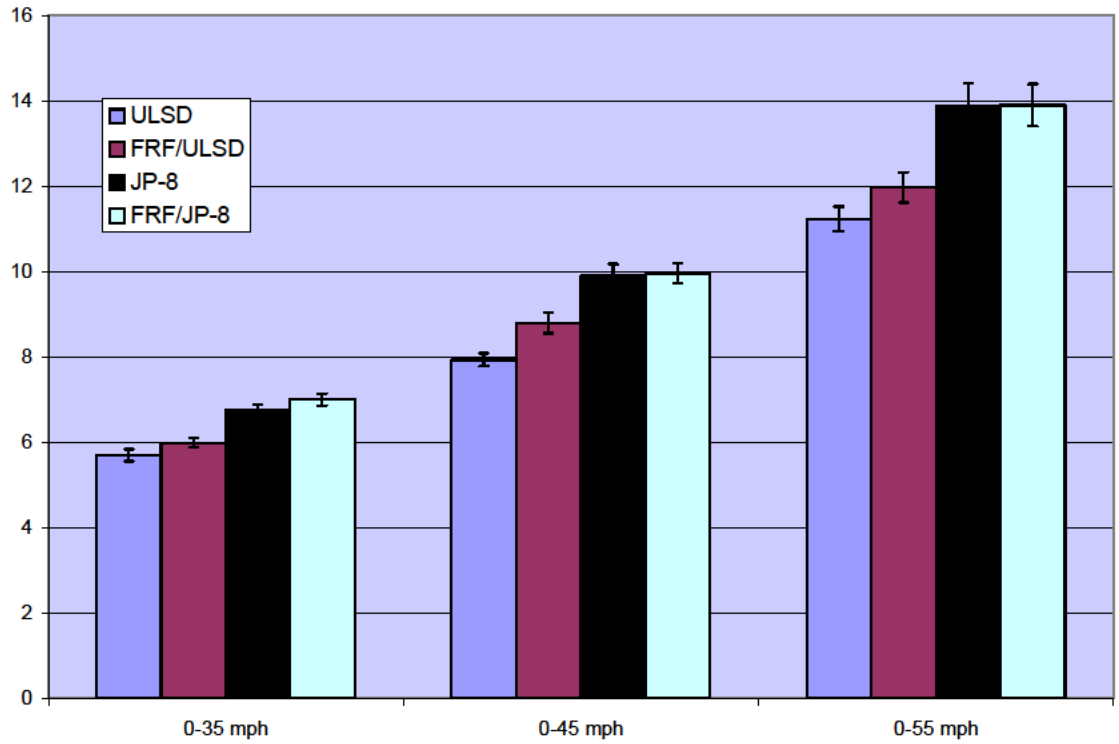



**Figure E1. 1996 ¾-Ton Chevrolet Pickup Truck Acceleration Runs**

The TFLRF pickup truck, powered by a 6.5L(T)(E) diesel engine was fueled with original formulation FRF. The original formulation FRF is a blend of 84%v off-road diesel fuel, 10%v water, and 6%v Schercomid emulsifier. The vehicle was used only on-campus in stop-and-go service, and accumulated approximately 100 miles per month. TFLRF testing with this vehicle has stopped because of starting and drivability problems related to effects of the fuel blends' opacity on a critical optical engine timing sensor. Several technical solutions related to reprogramming the engine controller or modifying critical components in the engine are possible, but not desirable for several reasons. Potential solutions to clarify the fuel related to changing the fuel preparation technique or additional additives are also being considered.

Weekly fuel sampling that was conducted to monitor FRF stability during July 2008 (Figure E2).

**Figure E2. Periodic Fuel Samples from HMMWV Fuel Tank (July 2008)**

The five samples shown in Figure 3E2 are all part of the same batch of fuel; all came from the same drum of fuel, but were taken as samples at different locations and times. The sample on the left was drawn from the barrel on 7 July 2008. The other four were all drawn from the vehicle's fuel tank, on 7 July, 14 July, 21 July and 29 July. The right-most sample was drawn after the vehicle was refueled. Although some progressing color change is evident in the fuel from the vehicle tank, and all are darkened as compared to the sample drawn from the fuel drum, there is no apparent separation of the water or surfactant. The color change is likely caused by the fuel dissolving residue from the engine and tank as it circulates.

The HMMWV running on FRF was driven more-or-less daily until September 10, when it was deadlined for a front suspension problem that caused the vehicle to be unstable. The vehicle was transported to a repair facility offsite on September 15. The front suspension problem was diagnosed and remedied by the replacement of an idler arm and a pitman arm. The fuel level sensor was also replaced. Examination of the failed sensor revealed the absence of some electrical parts, which rendered the sensor electrically inoperable. There is no indication that the failure is related to the fuel and, in fact, likely occurred prior to the vehicle's arrival at SwRI.

Weekly fuel sampling to monitor FRF stability continued up to the vehicle's transfer for repair (Figure E3).


**Figure E3. Periodic Fuel Samples from HMMWV Fuel Tank (September 2008)**

The samples shown in Figure E3 are all part of the same batch of fuel; all came from the same drum of fuel but were taken as samples at different locations and times. The sample on the left was drawn from the barrel on July 7, 2008. The others were drawn from the vehicle's fuel tank, on September 4 and September 16. The sample on the left is the same container that was on the left in similar pictures in previous reports, for comparison. All samples are clear, with no apparent sediment, separation or gelling. Any color differences apparent in Figure E3 are effects of the lighting and different-sized sample containers; there is no color variation appreciable to the eye.

The HMMWV running on FRF returned from repair on October 2, and resumed its role in daily testing of startability and drivability using Fire Resistant Fuel. To date, the HMMWV has logged 333 miles on FRF. The 50 gallons of fuel prepared for this testing was consumed by the vehicle, so new fuel was mixed. As no fuel-related issues were observed using the previous fuel, a new blend containing 125 ppm Mist Control Additive was prepared for testing, and the vehicle tank was filled with the new fuel on October 16. There have been no issues with driveability or starting, though the vehicle did start somewhat less quickly, and there was indication (poor idling quality, smell of unburned fuel, light smoke) upon startup.

Weekly fuel sampling resumed. Figure E4 shows the samples taken since the vehicle was returned from repair. The samples shown are all part of the same batch of fuel; all came from the same drum of fuel but were taken as samples at different locations and times. The sample on the left was drawn from the barrel on October 16, 2008. The others were drawn from the vehicle's fuel tank, on October 20, October 29, and November 3, respectively. There was no apparent sediment, separation or gelling, but the samples were increasingly cloudy.


**Figure E4. Periodic Fuel Samples from HMMWV Fuel Tank (October 2008)**

The HMMWV running on FRF logged 364 miles on FRF. The vehicle was running on a blend including 125 ppm, Mist Control Additive. There were no issues with drivability or starting, though the vehicle did start somewhat less quickly, and there was indication of poor combustion (poor idling quality, smell of unburned fuel, light smoke) upon startup.

Figure E5 showed the fuel samples taken during the month of November 2008. The samples all came from the same drum of fuel but were taken as samples at different locations and times. The sample on the left was drawn from the barrel on 16 October 2008, and was stored indoors under controlled conditions. The others were drawn from the vehicle's fuel tank, on 3 November; 12 November; 17 November; 24 November; and 1 December, respectively. All samples other than the one drawn from the drum were cloudy to some degree, though there was no discernible trend. No separation, sedimentation or gelling was apparent.


**Figure E5. Periodic Fuel Samples from HMMWV Fuel Tank (November 2008)**

The HMMWV running on FRF had accumulated 368 miles on FRF. The fuel in its tank was a blend that included 125 ppm, Mist Control Additive. The vehicle had been out of service for nearly a month while new batteries were on order.

Figure E6 shows the fuel samples taken during the month of December 2008. The samples all came from the same drum of fuel but were taken as samples at different locations and times. The sample on the left was drawn from the barrel on 16 October 2008, and had been stored indoors under controlled conditions. The others were drawn from the vehicle's fuel tank, on 1 December, 15 December, 22 December and 29 December, respectively. All samples were apparently clear, with no separation, sedimentation or gelling observed.


**Figure E6. Periodic Fuel Samples from HMMWV Fuel Tank (December 2008)**

As of April 2009, the HMMWV operating on JP-8 FRF + 125 ppm MCA had accumulated 530 miles on the test fuel.